EVALUATION OF AERODYNAMIC SOFTWARE IN THE HYPERSONIC FLOW REGIME

TASK5 - FINAL REPORT - Revision 1
Contract number W7701-053774/001/BAL
DRDC Valcartier contract report CR 2007-247

Scientific authority :

Francois Lesage
DRDC Valcartier

Prepared by :

Nicolas Parisé
MAYA Heat Transfer Technologies LTD.
4999-400 Ste-Catherine St. W.
Montréal, QC
Canada H3Z 1T3

August 20, 2007

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1. Introduction

Time critical targets such as mobile missile launchers can move to site, prepare and launch in 30 minutes. C4ISR and IT improvements have allowed compression of the engagement timeline of such targets so that weapon delivery time has become significant. A favored option to defeat time-critical targets is that of a hypersonic missile (flight speed greater than Mach 5) launched from a stand-off position. A project recently initiated has for objective to develop, demonstrate and validate a capability to evaluate and analyze enabling technologies of hypersonic missiles. This capability will be applicable to a range of hypersonic missile missions characterized by long-range time-critical engagements. One key technology specific to hypersonic missiles is the accurate prediction of vehicle aerodynamics.

Current prediction methods include theoretical and semi-empirical aerodynamic prediction software used to calculate the full aerodynamic coefficients of missile-like platforms without having to resort to a full numerical simulation (CFD) or actual flight testing. These codes have capabilities to predict aerodynamic coefficients in the high supersonic and hypersonic flow regimes. Theoretical approaches such as the second-order shock-expansion theory as well as the Newtonian flow theory are used for these flow regimes.

The goal of the current project is to evaluate the accuracy of aero prediction tools in predicting main aerodynamic coefficients in the range between Mach 3 and 8. To achieve this, seven flight configurations, which have been tested experimentally, are used in a comparative study. The main aeroprediction codes used for this study are Prodas V3, Datcom, AP05. They are compared between Mach 3 and 8, and focus is made on accuracy in predicting major aerodynamic coefficients : Cx, Cna and Cma. In addition to these codes, results from SHEMA and Interact are used to illustrate the relative accuracy on predicted pressure distribution on the configurations.

2. Methodology & Description of evaluated software

2.1 Methodology and Configurations

The general methodology is to use the aero prediction codes as directed in their user manuals and output the following aerodynamic coefficients between Mach 3 and 8 : Cx, Cna and Cma. The reference geometry was respected as much as permitted when defining it in the aeroprediction codes. Small meplats and radii were included in the models, when the information was made available in literature.

The first configuration used in the evaluation is the CAN1 test configuration, as shown in Fig.1. This is a basic cone-cylinder-flare configuration. Dimensions are given in Ref 1. This configuration was tested in the DRDC-V aeroballistic test range and a complete set of aerodynamic coefficients was generated between Mach 3.78 and 4.49. For this configuration, the center of gravity (CG) is located 3.45 calibers from the nose (1cal = 18mm), and all aerodynamic moment coefficients are given about the CG.

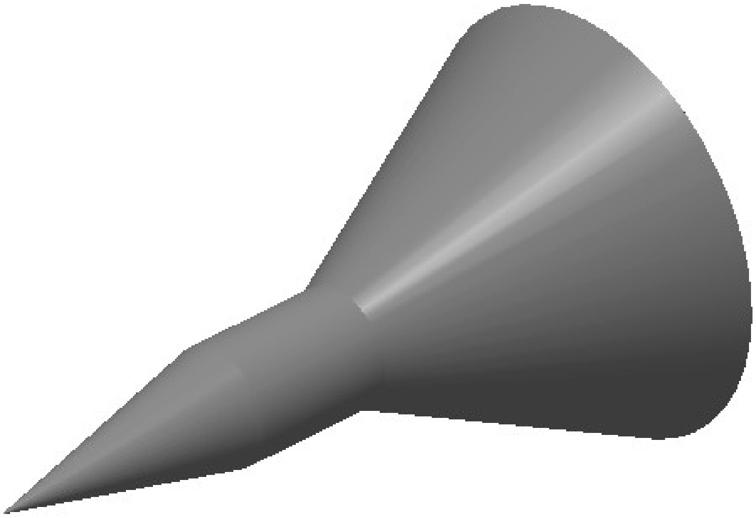


Fig 1 - CAN1 Configuration

The second configuration used in the evaluation is the CAN3 test configuration, as shown in figure 2. This configuration was shown to generate hypersonic heating problems due to jet impingement on the fin leading edge (Ref 2). This is a cone-cylinder-flare-fin configuration. Dimensions are given in Ref 2. This configuration was tested in the DRDC-V aeroballistic test range and in free-flight and a complete set of aerodynamic coefficients was generated at Mach 4.46. For this configuration the center of gravity is located 4.41 calibers from the nose of the projectile (1 cal = 20mm).

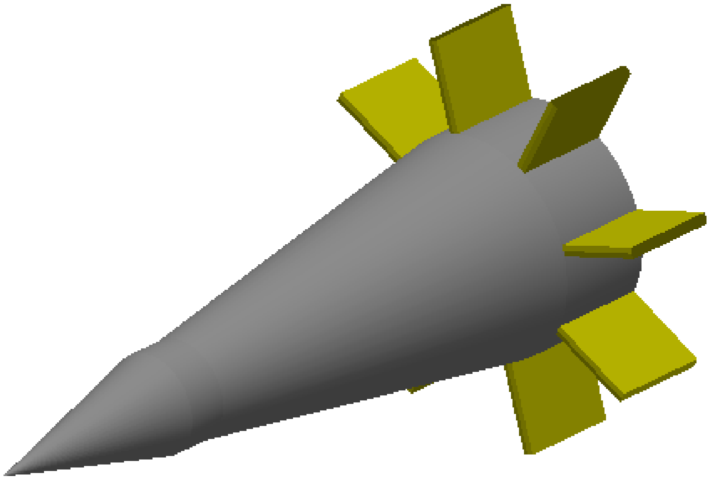


Fig 2 – CAN3 Configuration

The next configuration is the CAN4 test configuration, as shown in figure 3. This is a cone-cylinder-flare configuration. Dimensions are given in Ref 2. This configuration was tested in the DRDC-V aeroballistic test range and in free flight and a complete set of aerodynamic coefficients was generated between Mach 4.42 and 5.92. For this configuration the center of gravity is located 2.85 calibers from the nose of the projectile (1 cal = 18mm).

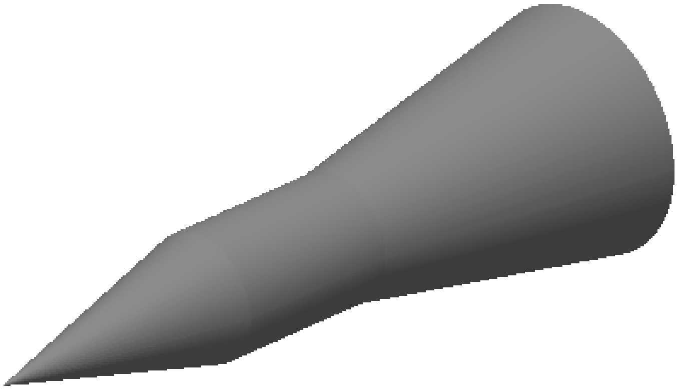


Fig 3 – CAN4 Configuration

The next configuration is the HB2 test configuration, as shown in figure 4. This is an ogive-cylinder-flare configuration. Dimensions are given in Ref 3. This configuration was tested experimentally and a complete set of aerodynamic coefficients was generated between Mach 2 and 8. For this configuration the center of gravity is located 1.95 calibers from the nose of the projectile (1 cal = 4in = 101.6mm).

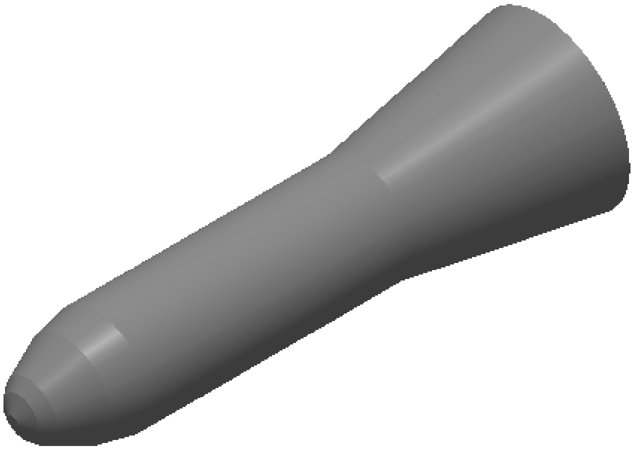


Fig 4 – HB2 Configuration

Figures 5 and 6 show two variants of the HEMi dart. The first one is a compressed version of the dart, which has a cone-cylinder-flare-cylinder-boat tail shape. The second one is the un-compressed version of the dart. No formal aerodynamic data exists for these configurations, but they will be evaluated with the aero prediction software to see hypersonic effects for these very high L/D configurations. The center of gravity for the compressed configuration is located 21.17 calibers from the nose of the projectile (1 cal = 30mm). The center of gravity for the un-compressed configuration is located 29.63 calibers from the nose of the projectile (1 cal = 30mm).

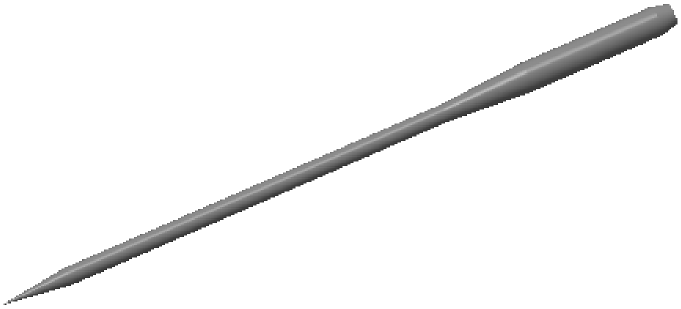


Fig. 5 - HEMi – Dart Compressed

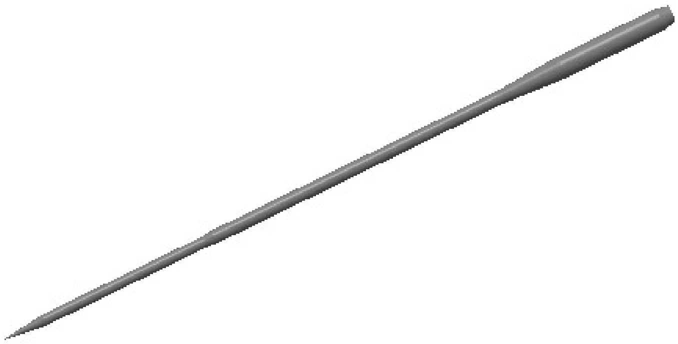


Fig. 6 - HEMi – Dart Un-compressed

Finally, the RARDE cone-cylinder-flare configuration has extensive data. Figure 7 shows this configuration. This configuration served to measure aerodynamic heat fluxes at hypersonic Mach numbers. In addition, measurements were made for the coefficient of pressure. Dimensions are given in reference 4. The center of gravity for this configuration is located 13.67 calibers from the nose of the projectile (1 cal = 10.2mm).

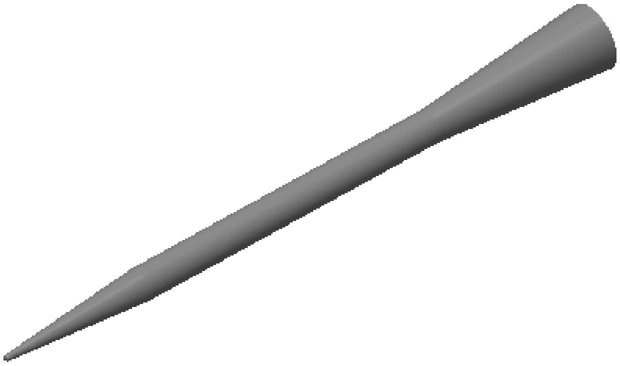
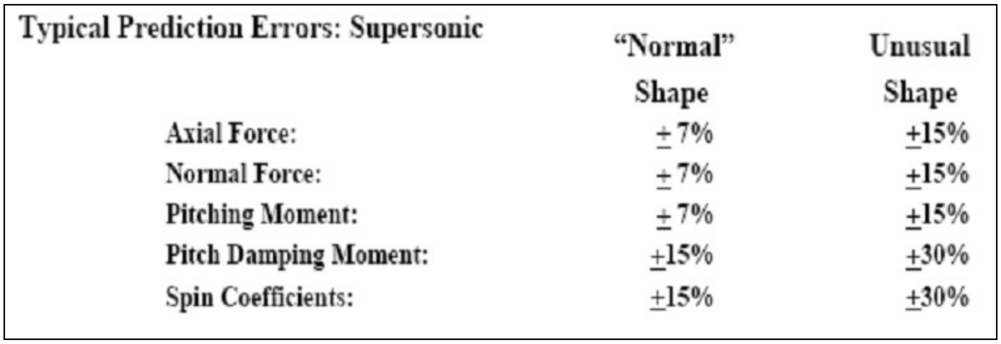


Fig. 7 – RARDE Configuration

2.2 Description of Evaluated Software

2.2.1 Prodas

Prodas is a complete projectile design software with tools for mechanical design, aerodynamic characterization and trajectory evaluation. The aerodynamic coefficient database is an extensive collection of test data and empirical data. The aerodynamic database is divided in two main codes, one for spin-stabilized projectiles and the other for fin-stabilized models. Typical prediction errors for fin-stabilized projectiles, in the supersonic regime, are listed in the table below :



Typical Prediction Errors: Supersonic	"Normal" Shape	Unusual Shape
Axial Force:	±7%	±15%
Normal Force:	±7%	±15%
Pitching Moment:	±7%	±15%
Pitch Damping Moment:	±15%	±30%
Spin Coefficients:	±15%	±30%

Ref : Prodas Training Material

2.2.2 AP05

The NSWC Aeroprediction code uses a combined empirical and theoretical approach to compute the main aerodynamic coefficients for projectiles and missiles. As for Prodas and Datcom, AP05 allows the user to define complex projectile geometries, including fin sets. It also includes a trajectory prediction capability.

2.2.3 DATCOM

The Missile Datcom code has various routines to define the aerodynamic geometry and calculate the detailed aerodynamic coefficients for various configurations. The aerodynamic coefficient calculation is done with various theoretical methods. An interesting feature is the fact that user can switch between theoretical methods in the hypersonic regime with a choice between the Second Order Shock-Expansion theory (SOSE) and the modified Newtonian approach. Full details on DATCOM are given in Reference 8.

2.2.4 Interact

Interact is an aerothermodynamic design code for axisymmetric projectiles, that uses a viscous-inviscid interaction scheme to evaluate external flow and the ensuing heat transfer to the surface. Separate solution procedures for the inviscid (Euler) and the viscous (boundary layer) fluid dynamic equations are coupled by an iterative solution procedure. The more recent versions of Interact include real gas effects, namely nonequilibrium and equilibrium boundary layer equations. The projectile near-wall treatment, representing a converged solution for both the inviscid and viscous equations is obtainable in seconds on modern computers. The method was validated on various configurations such as flat plates, blunt cones and typical projectile geometries such as a cone-cylinder-flare for Mach numbers from 1.5 to 10.5. A nice feature in Interact is its flexibility in applying different technique to solve the inviscid flow equations. Potential methods, 1st and 2nd order shock-expansion and Newtonian methods are available. A major drawback is its inability to treat complex geometries. The code is limited to only one flare region. More details on Interact can be found in References 5 and 6.

2.2.5 SHEMA

The SHEMA (Supersonic-Hypersonic Engineering Method for Aeroheating) codes were developed through a joint SNC TEC – Université de Sherbrooke research project. Essentially, the codes utilize a similar approach to Interact, where full flowfield calculations are made, and then the near wall flow properties are used to calculate heat transfer from the fluid to the wall. Contrary to Interact though, the method used to solve the Euler equations is a full 2D axisymmetric numerical method, whereas Interact uses theoretical methods. It is possible to say that for calculation of the inviscid flow, the SHEMA code is more appropriate. However, Interact has the capability of solving the boundary layer equations from the inviscid results. SHEMA does not treat the viscous flow, but rather consider that the conditions computed at the wall in the inviscid flow can be used as being the flow conditions just outside the boundary layer. This allows for determination of the wall heat transfer with approximate methods such as the reference enthalpy method and the Reynolds Analogy Method. Another very interesting feature of the SHEMA code is the ability to estimate wall ablation under the application of various heat fluxes. A more detailed explanation of the SHEMA codes is made in Reference 7

3. Results

For all seven test configurations, Cx, Cna, Cma are given as a function of Mach number and compared to test data, when available. For Datcom, two result sets are given, one using the Second-Order Shock-Expansion theory (SOSE), the other being based on the Newtonian flow theory (HYPER). AP05 results are using either the SOSE or the Newtonian flow theory, depending on a cutoff Mach number defined by the user. In all cases, this cutoff Mach number was set at Mach 5. Finally, PRODAS uses a semi-empirical method that compiles experimental results and extrapolates them to the configuration of interest based on several parameters (ogive length, body length, etc.)

3.1 CAN1 Configuration

3.1.1 Main Aerodynamic Coefficients

Figures 8 to 10 give the CA0, Cna and Cma distributions for the CAN1 configuration.

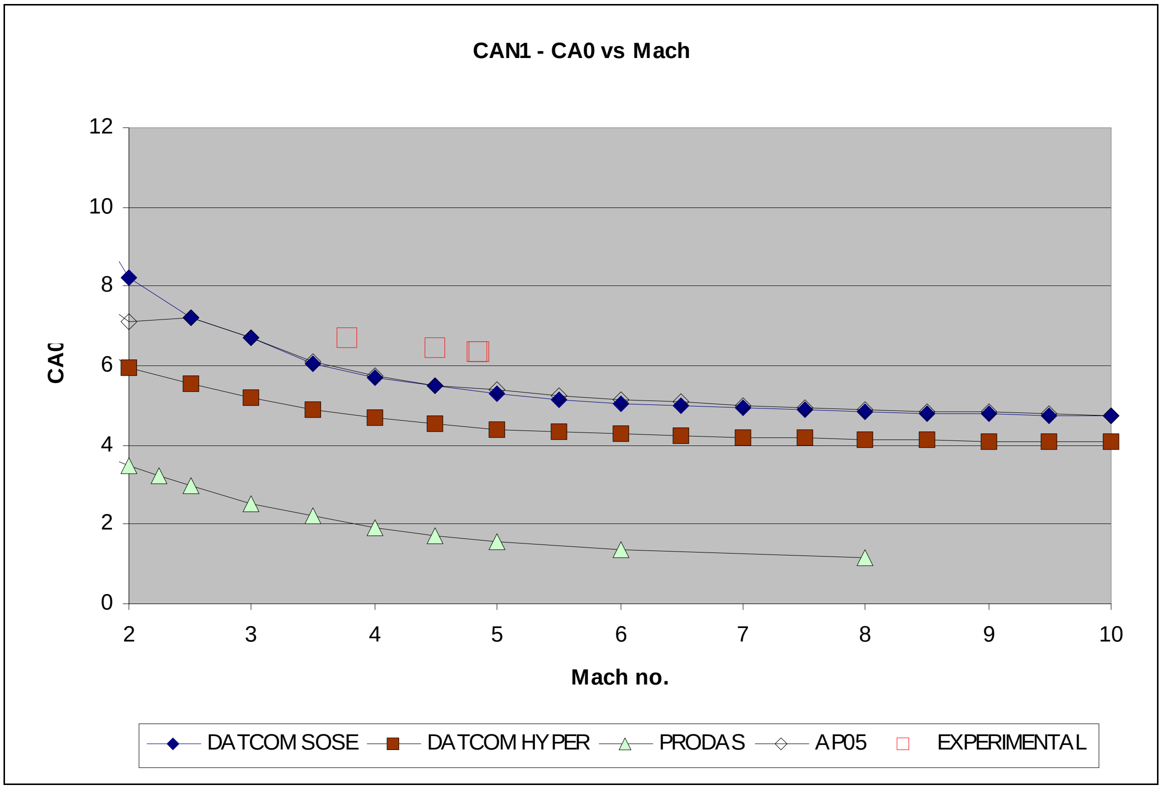


Fig. 8 – CAN1 – CA0 vs. Mach

- AP05 & DATCOM SOSE are closest to the experimental results. They both use a shock-expansion method at these Mach numbers

- Base drag included in all data above.

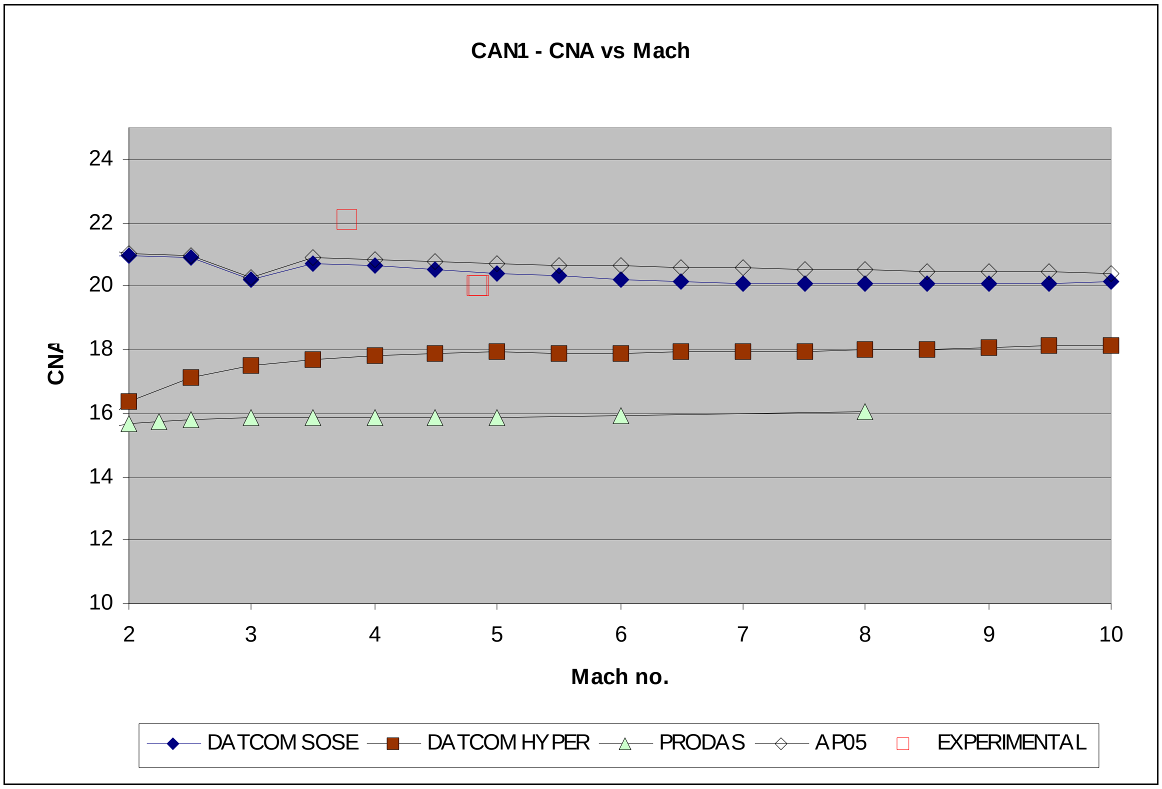


Fig. 9 – CAN1 – CNa vs. Mach

- Both DATCOM and AP05 SOSE methods succeed very well at predicting an accurate Cna.

- If we extrapolate on results, the Newtonian flow theory will give better results for higher Mach numbers, over Mach 6.

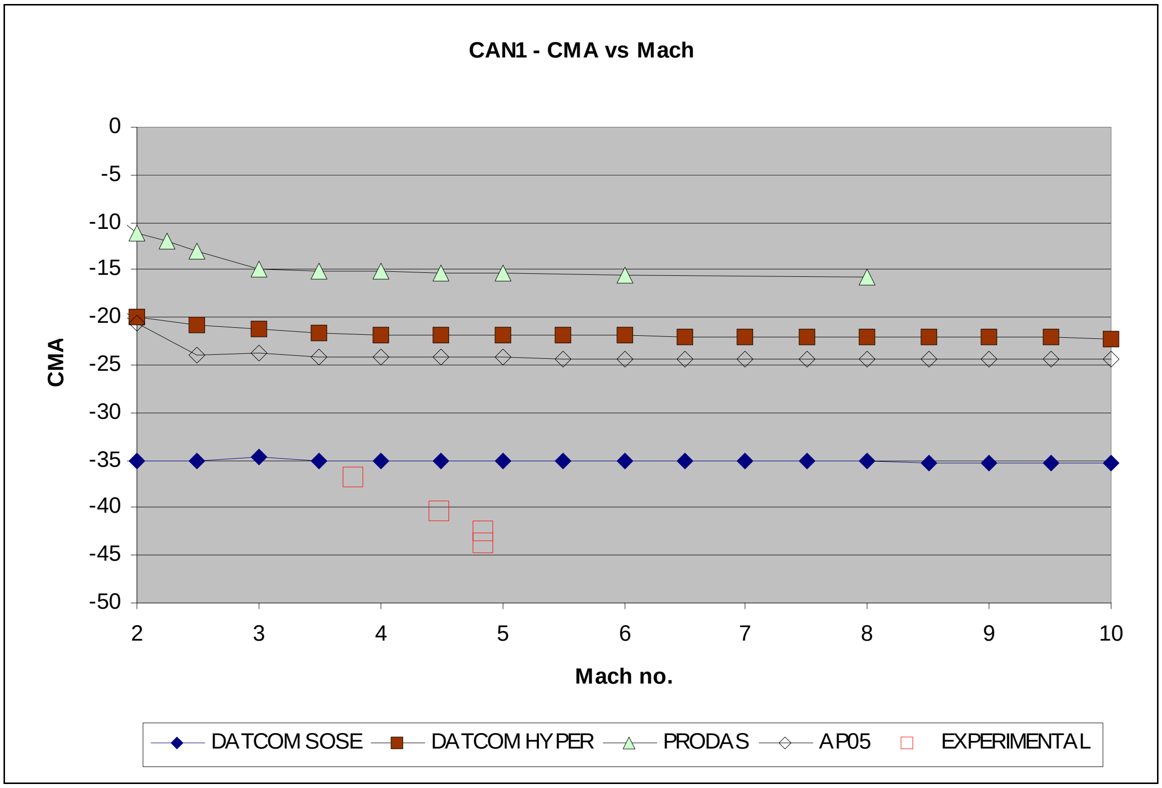


Fig. 10 – CAN1 – CMa vs. Mach

- CMA is computed at projectile center of gravity.
- The DATCOM SOSE method is the only one that predicts Cma values near the experimental results
- All methods end up leveling off on a plateau, while the experimental data shows an increase in stability between Mach 3 and 5
- Overall, the aero prediction methods give conservative stability results.

3.1.2 Pressure Distributions

Figures 11 and 12 give the pressure distributions on the CAN1 projectile at various Mach numbers. Figure 12 gives a comparison on pressure distributions between AP05, DATCOM and SHEMA at Mach 4 and 5.5. We observe that AP05 is closer to the SHEMA results than DATCOM. SHEMA offers a full numerical solution of the Euler equations and has been validated with full Navier-Stokes solvers, so constitutes a good comparison point. An interesting point to notice is the offset between AP05 and DATCOM in Figure 12. DATCOM pressure coefficients are generally lower than the ones predicted by AP05 everywhere on the projectile, expect at the body where the trend is reversed. However, looking at the aerodynamic coefficients, especially the CA0 results in Fig. 8, the curves are identical almost everywhere. To better analyze this effect, Table 1 shows the base drag prediction from both codes. We notice some offset at Mach 5.5, but the base drag numbers are the same at Mach 4. This does not explain why the CA0 results are the same with such an offset in pressure distributions. Investigating the way the codes incorporate friction drag in the drag estimate is recommended.

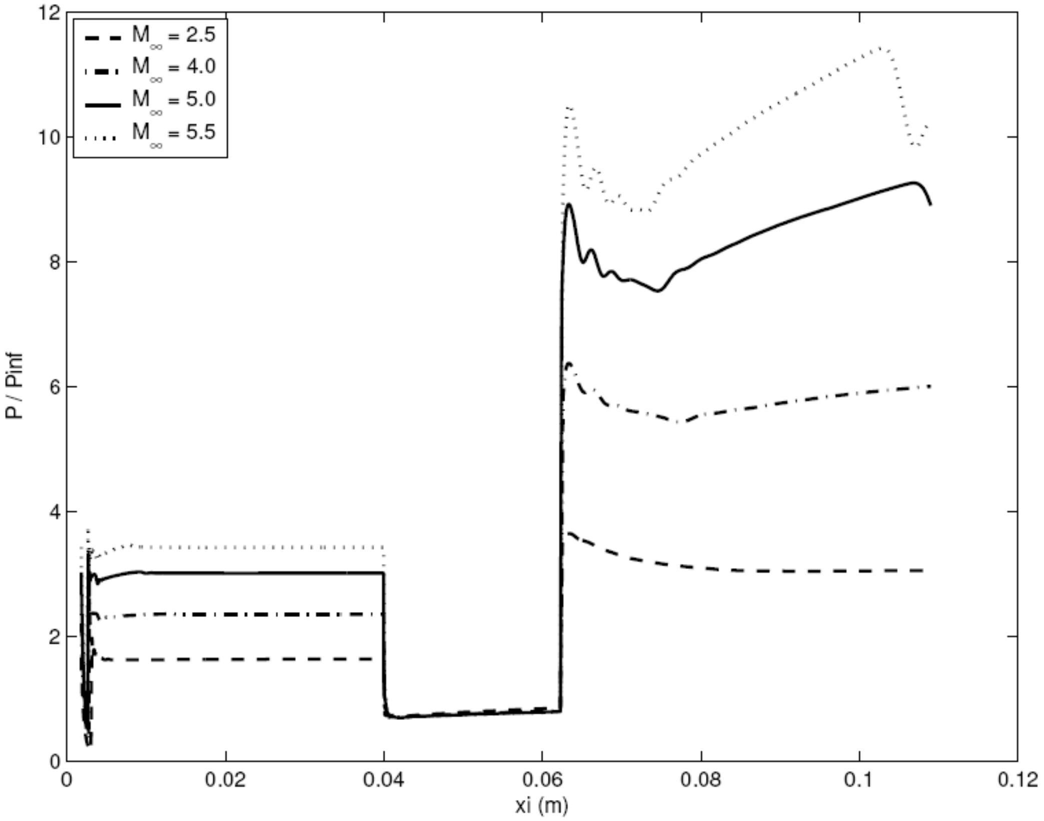


Fig. 11 – CAN1 Pressure Distribution (SHEMA)

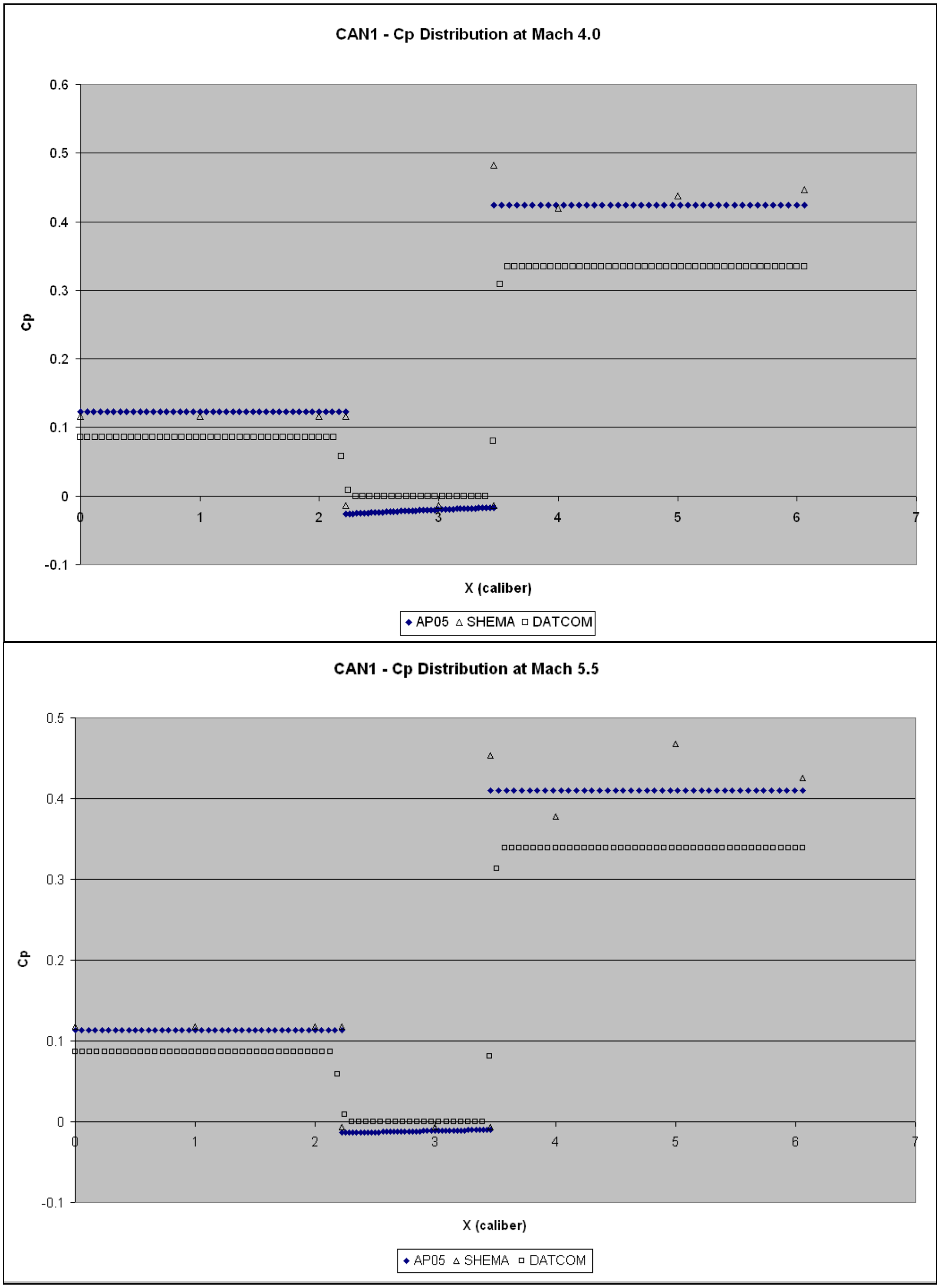


Fig. 12 – CAN1 Pressure Distribution – SHEMA, DATCOM & AP05 Results

Table 1 – Base Drag Prediction

Mach No.	AP05 Base Drag Coefficient	DATCOM Base Drag Coefficient
3	1.397	1.397
4	0.784	0.796
5	0.556	0.490
6	0.421	0.341
7	0.327	0.250
8	0.258	0.181
9	0.206	0.151
10	0.164	0.123

3.2. **CAN3 Configuration**

3.2.1 Main Aerodynamic Coefficients

Figures 13 to 15 give the main aerodynamic coefficient variation with Mach number for the CAN3 projectile. This is compared with experimental data measured by DRDC.

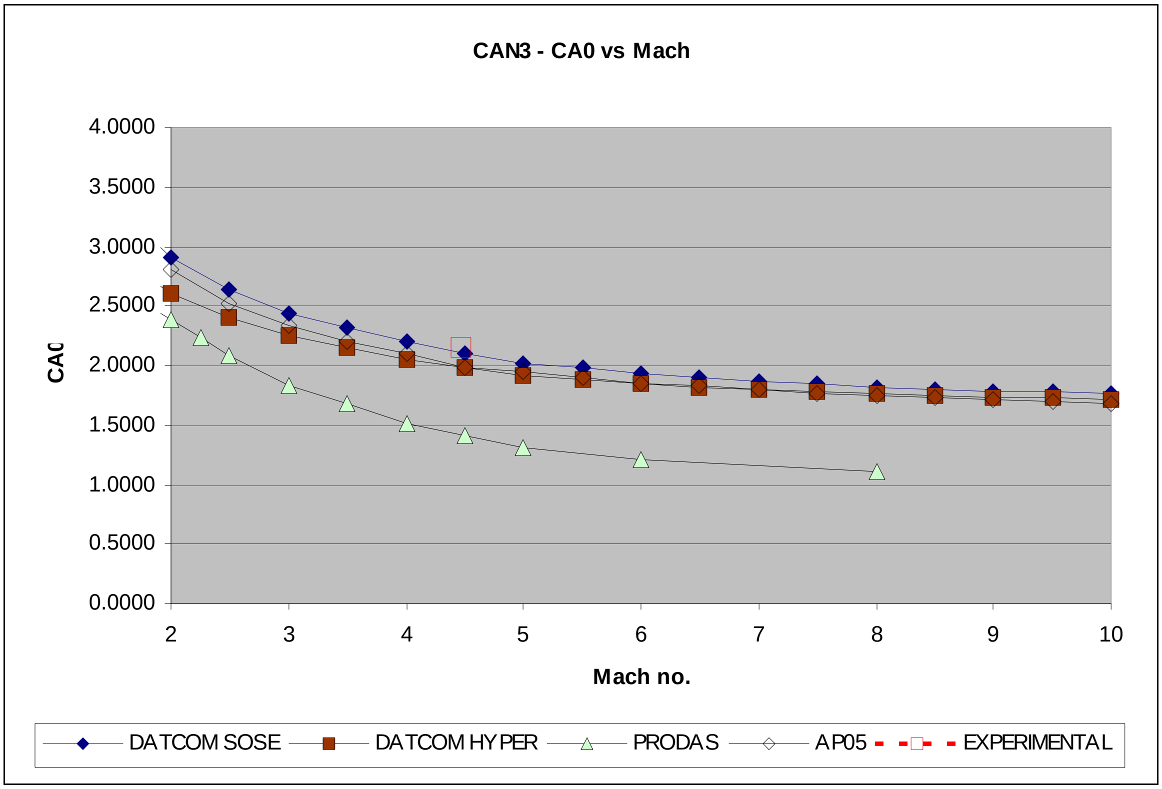


Fig. 13 – CAN3 – CA0 vs. Mach

- Base drag included in all data above.
- DATCOM SOSE is closest to test data for CA0. Again, SOSE seems to be the most accurate method.
- The main difference is probably due to the way the codes treat the fins.
- AP05 and DATCOM results converge together after Mach7.
- Prodas results have a significant offset with regard to test data.

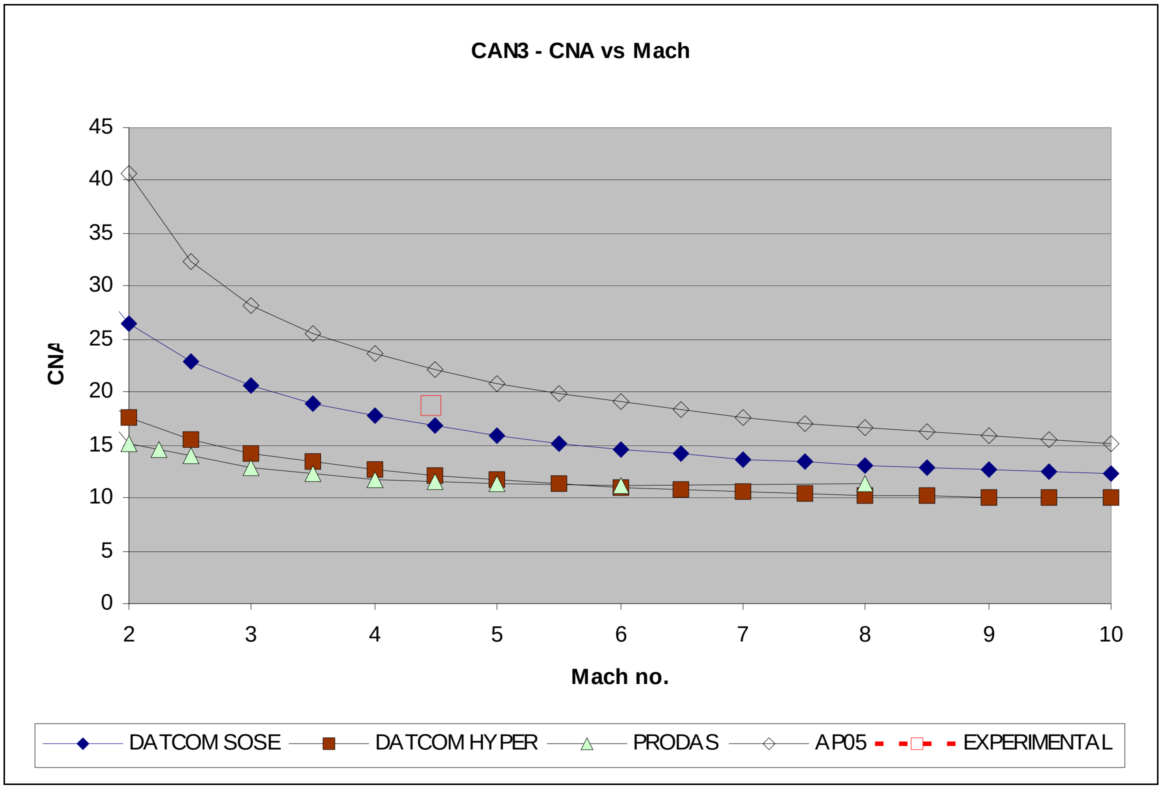


Fig. 14 – CAN3 – CNA vs. Mach

- For the Cna variation, DATCOM SOSE is very close to experimental data. We see that AP05 is also close to the test data.
- All codes show similar variations of Cna with Mach number. We note that PRODAS results are very close to the Newtonian theory method used by DATCOM hyper.
- The offset in results for the SOSE methods is probably due to the way the codes treat the fins.

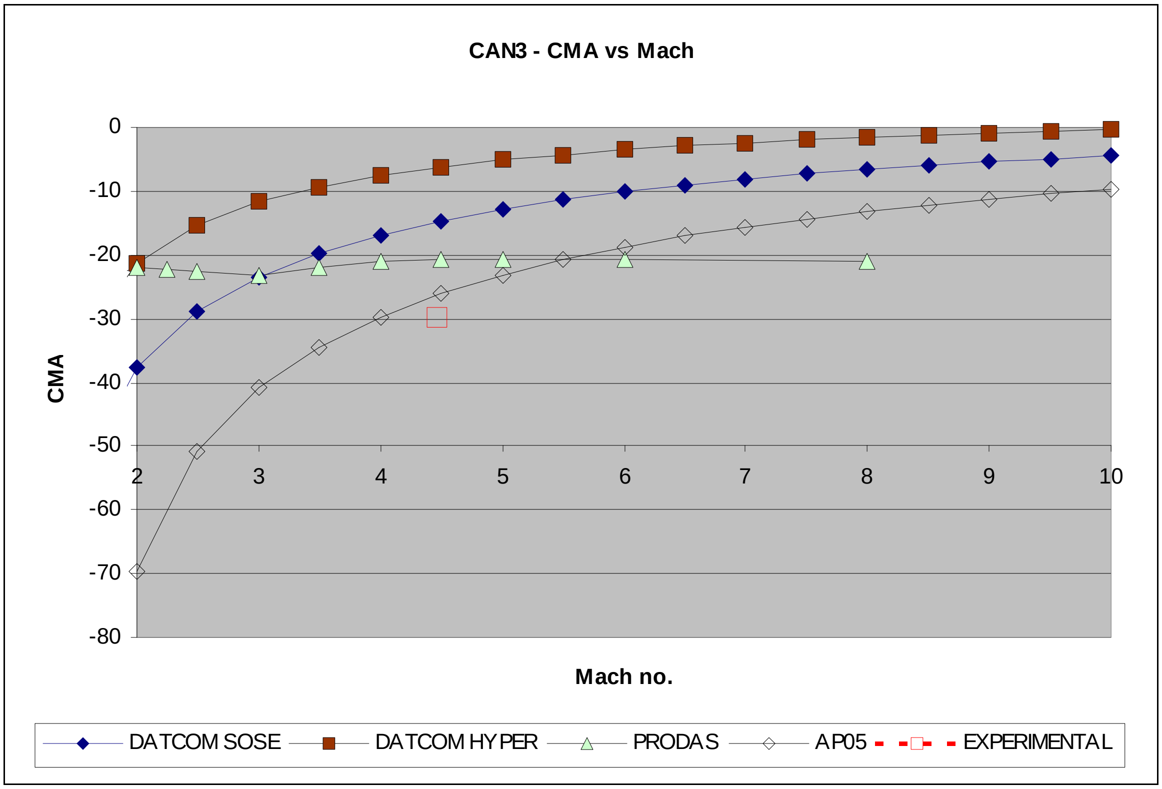


Fig. 15 – CAN3 – CMA vs. Mach

- CMA computed at projectile center of gravity.
- AP05 is the most accurate in predicting Cma when comparing to experimental data.
- All codes but PRODAS show a similar variation with Mach number
- Again, offset in the SOSE methods can be explained by differences in the way the codes treat the effect of fins.

3.3 CAN4 Configuration

3.3.1 Main Aerodynamic Coefficients

Figures 16 to 18 give the CA0, Cna and Cma distributions for the CAN4 configuration.

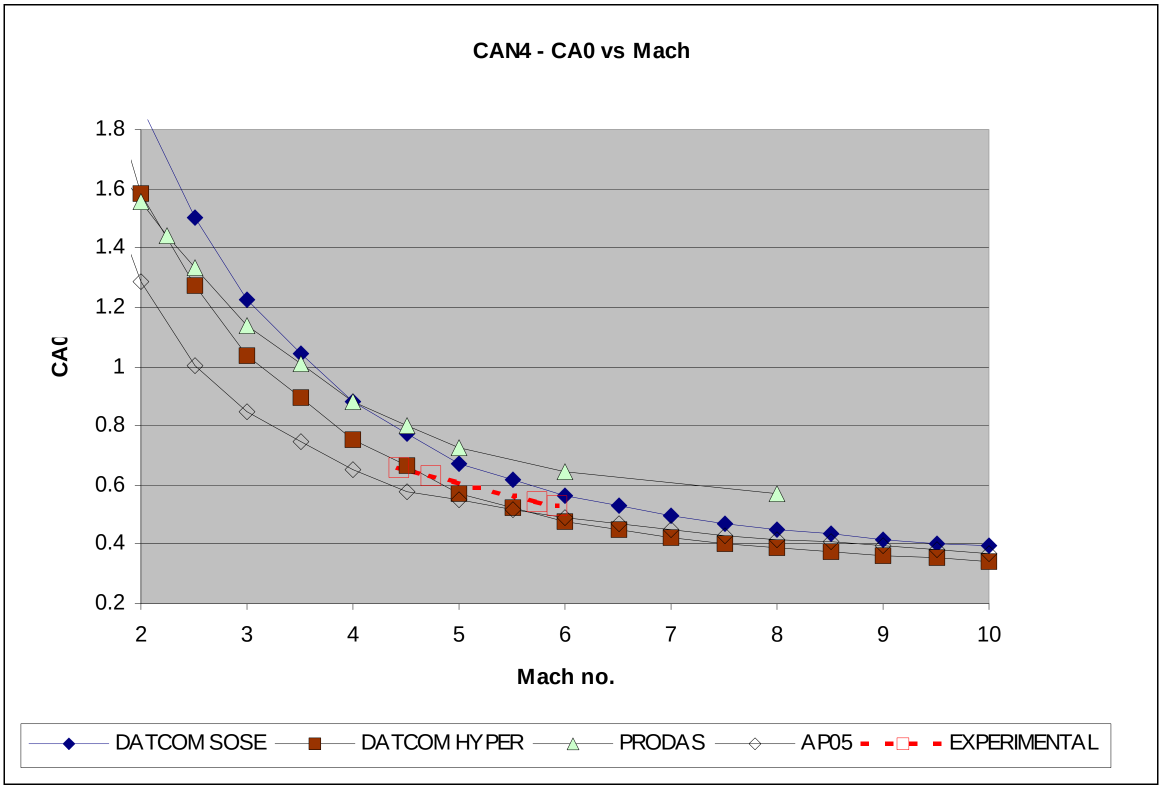


Fig. 16 – CAN4 – CA0 vs. Mach

- Base drag included in all data above.
- For this smaller flare angle, DATCOM HYPER methods show very good agreement with the experimental results, both in magnitude and variation with Mach number.
- Prodas over predicts the CA0, but to a lesser extent than what was seen for the CAN1 configuration

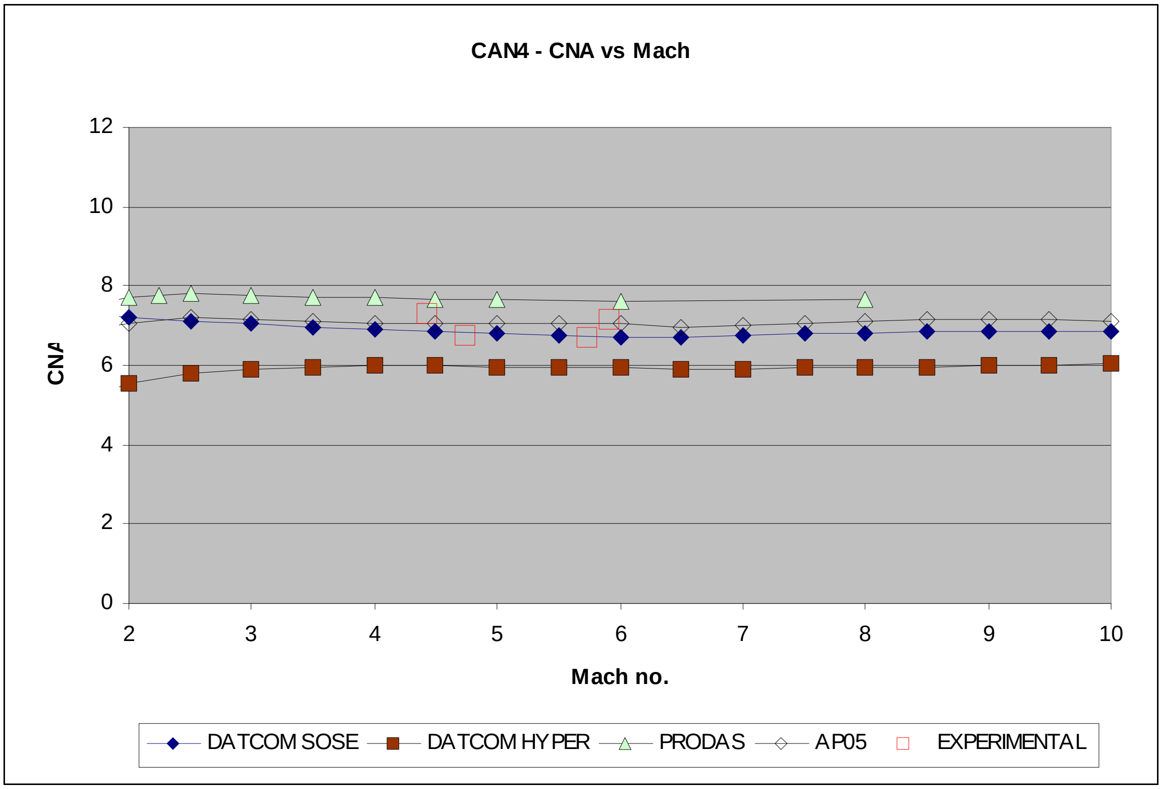


Fig. 17 – CAN4 – CNa vs. Mach

- DATCOM SOSE and AP05 methods show very good agreement with the experimental results.
- Prodas over predicts the test data again, but having a lower flare angle seems to be helping out its accuracy quite a bit.

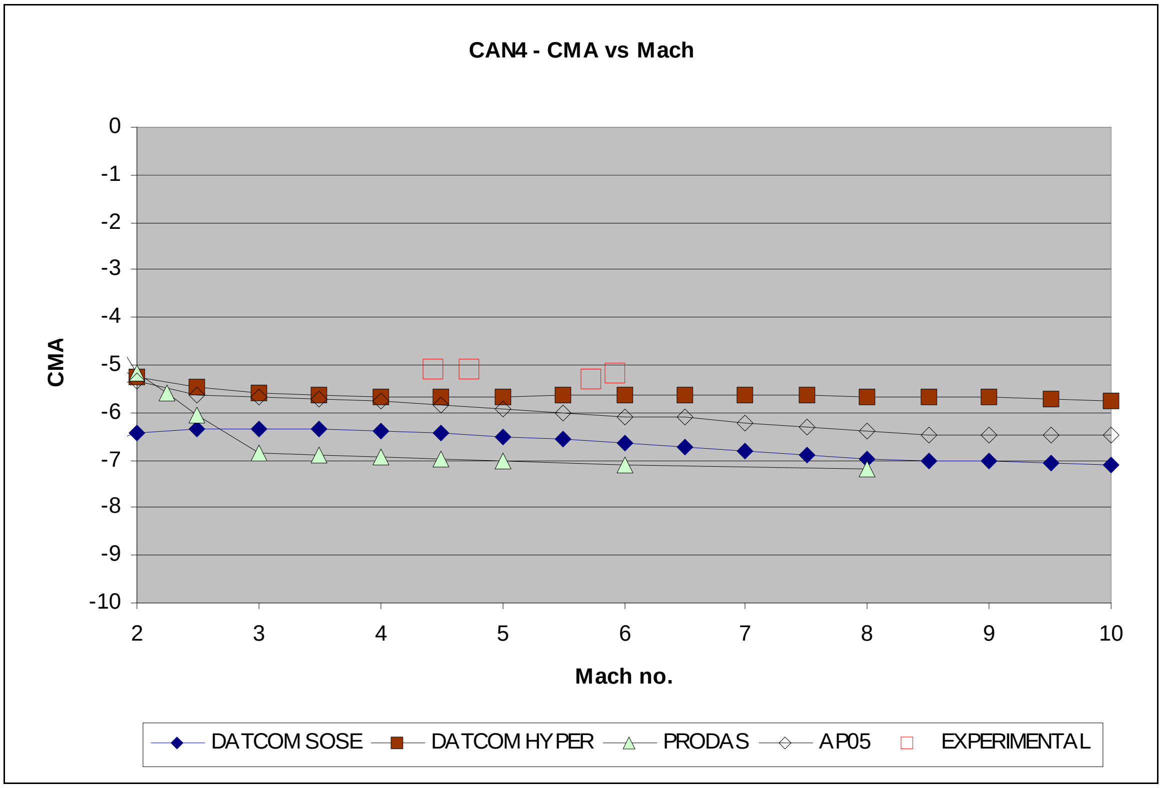


Fig. 18 – CAN4 – CMa vs. Mach

- CMA computed at projectile center of gravity.
- In this case, the DATCOM hypersonic method is closest to test data.
- Both SOSE methods also perform relatively well for the moderate hypersonic Mach numbers
- An important note, all methods over-estimate stability
- For this lower flare angle, we see that PRODAS is performing better compared to the other results.

3.4 HB2 Configuration

3.4.1 Main Aerodynamic Coefficients

Figures 19 to 21 give the CA0, Cna and Cma distributions for the HB2 configuration. This is a very interesting configuration because it has been tested in a wide range of Mach numbers, between Mach 2 and 10. This gives a better idea how the Newtonian theory behaves at larger Mach numbers.

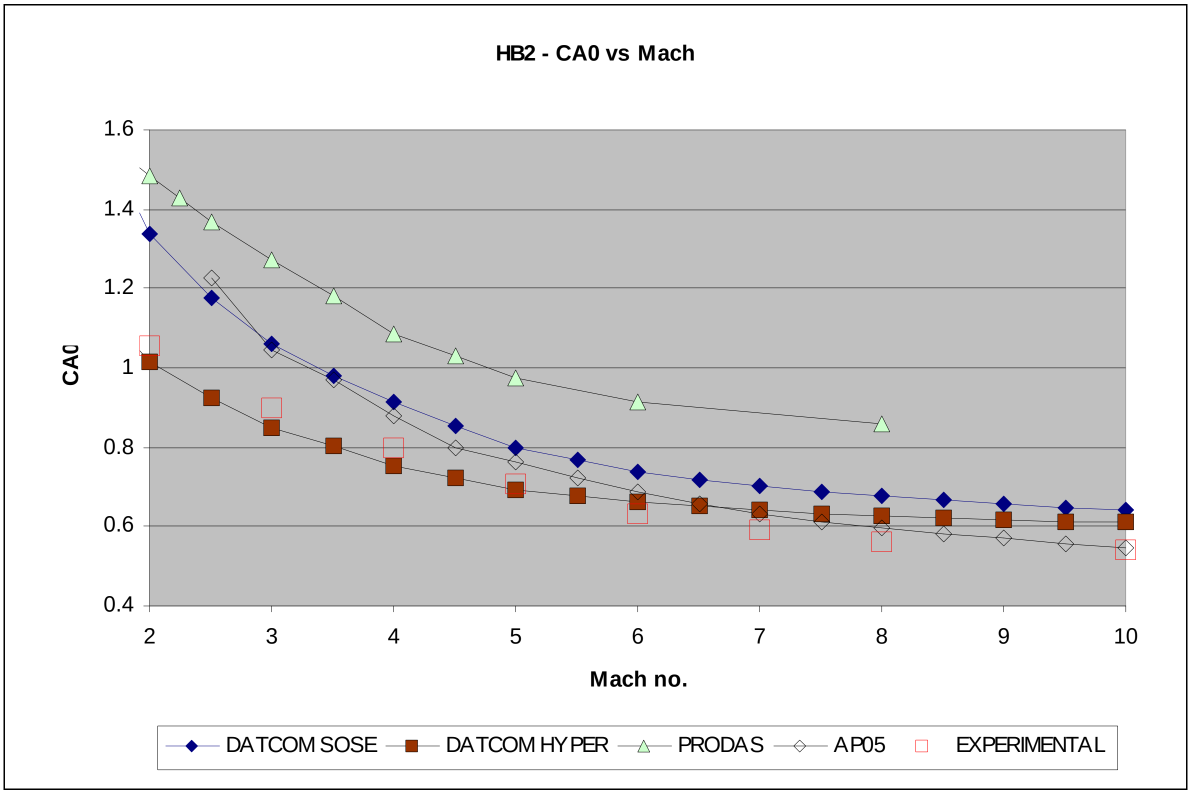


Fig. 19 – HB2 – CA0 vs. Mach

- Base drag included in all data above.
- AP05 and DATCOM give reasonably good results. Overall, AP05 follows the trend of the data curve with more fidelity at high Mach numbers.
- We note that the test data follows the DATCOM HYPER results until Mach 6, then the SOSE methods become more accurate.
- Prodas over estimates the results extensively, where we would expect this tool to perform quite well for this type of configuration.

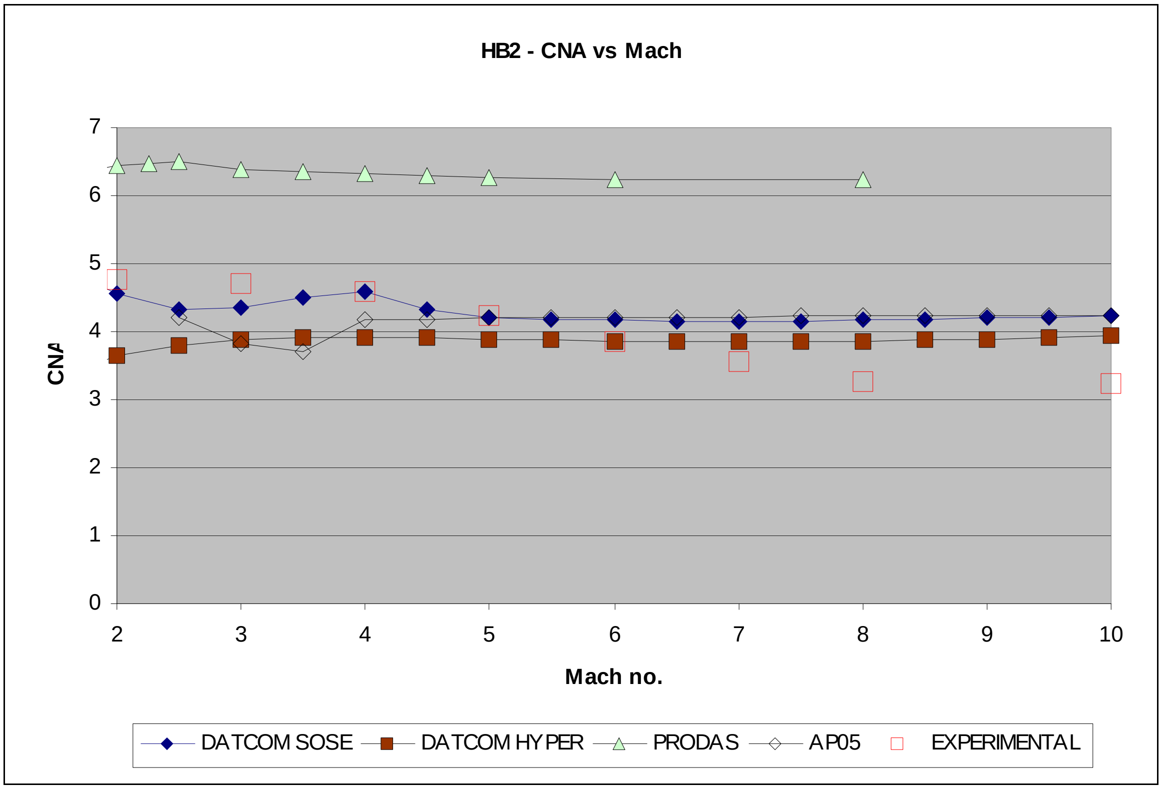


Fig. 20 – HB2 – CNa vs. Mach

- DATCOM SOSE gives the closest results up to Mach 5, then the HYPER method (Newtonian theory) is nearest the test data.
- Above Mach 5, the two DATCOM methods as well as AP05 results give very similar results.
- Prodas results overestimate the test data.

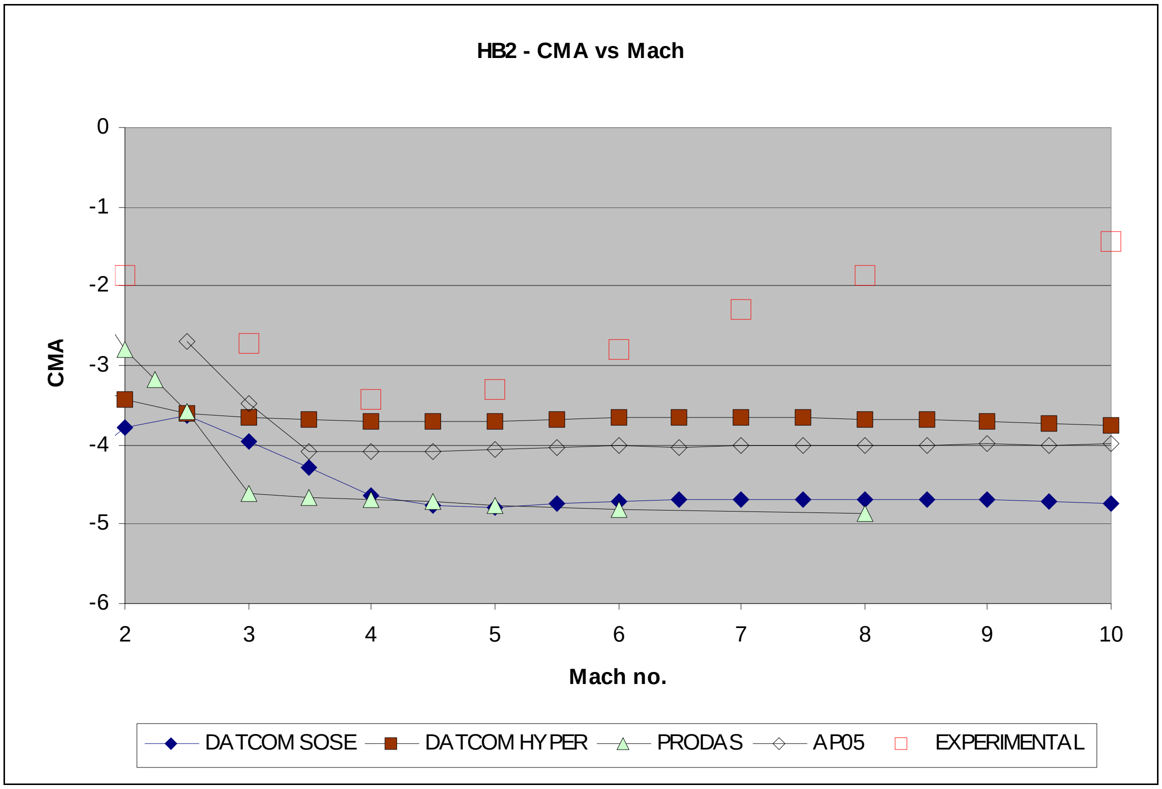


Fig. 21 – HB2 – CMa vs. Mach

- CMA computed at projectile center of gravity.
- All aeroprediction results are sensibly off the test data. No method captures the behavior above Mach 5.
- AP05, DATCOM SOSE and PRODAS show the right trend for CMA until Mach 5.
- All methods overestimate stability.

3.5 HEMi Configurations

3.5.1 Main Aerodynamic Coefficients

Figures 22 to 27 give CA0, Cna and Cma results for the HEMi dart, in both compressed and uncompressed configurations. No test data is available for these configurations, so the analysis below will be made on how the methods perform one compared to each other.

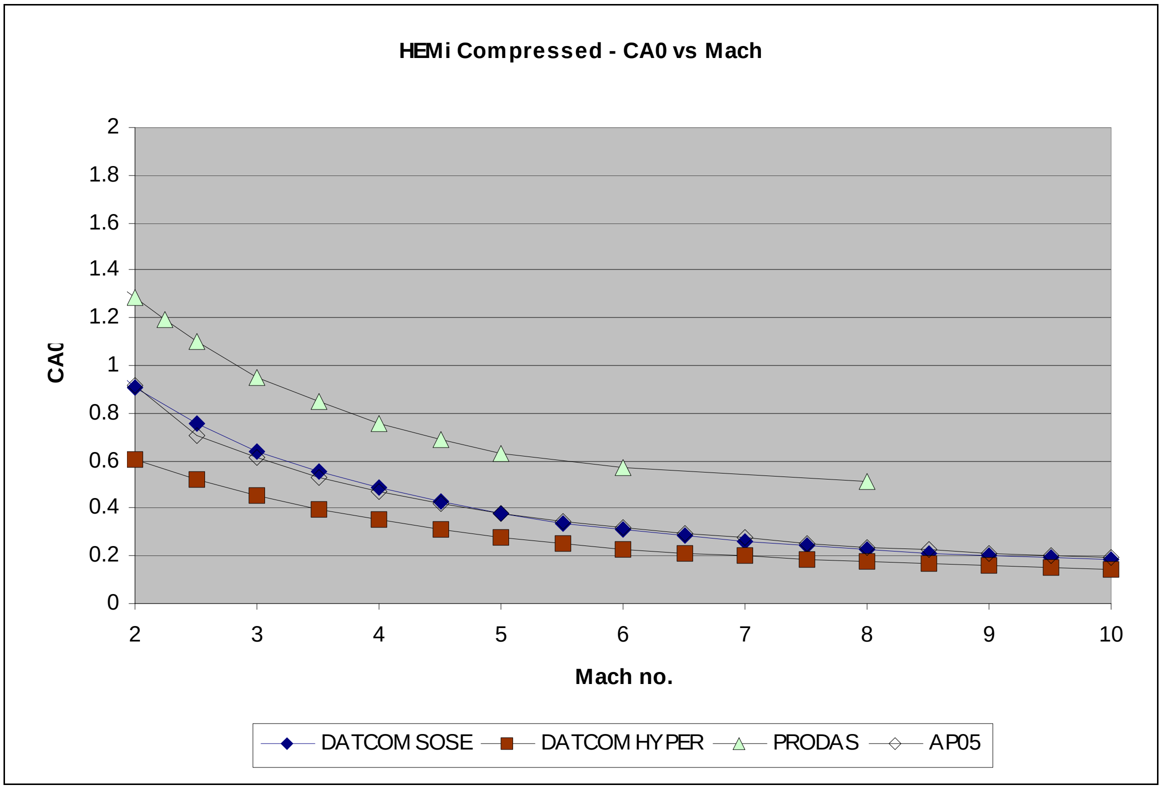


Fig. 22 – HEMi Compressed – CA0 vs. Mach

- Base drag included in all data above.
- SOSE methods compare very well one to another, even reaching values close to the Newtonian theory above Mach 7. Based on previous cases, these methods can be considered as the most accurate.

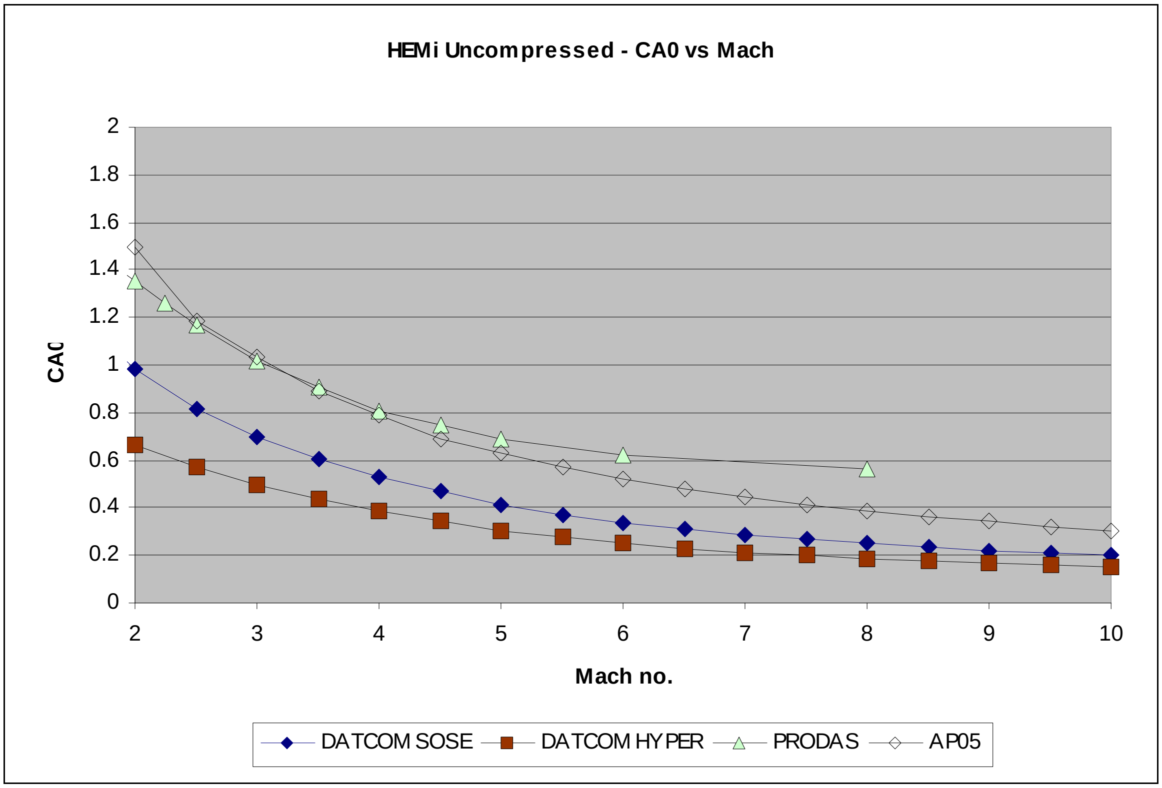


Fig. 23 – HEMi Uncompressed – CA0 vs. Mach

- Base drag included in all data above.

- In uncompressed mode, Prodas results and AP05 are almost coincident up to Mach 5. This was not noticed for previous models.

- With increasing length of the dart, it is expected that the CA0 increase slightly, not as much as what is seen for AP05 when comparing figures 22 and 23.

- All the other methods give results that increase slightly between the compressed and un-compressed configurations.

- The jump in CAO between compressed and uncompressed configurations noted for AP05 is investigated in more detail. Table 2 shows a comparison of drag contributors for the two configurations. It is clear that the viscous drag component has a large influence on the total drag coefficient and this prediction might be questionable.

Table 2 – Drag Components for HEMi Configuration

	Mach 5		Mach 7.5	
Drag Component	Compressed	Uncompressed	Compressed	Uncompressed
Pressure	0.109	0.124	0.084	0.103
Viscous	0.196	0.325	0.132	0.218
Base	0.077	0.182	0.040	0.095
Total	0.382	0.631	0.256	0.416

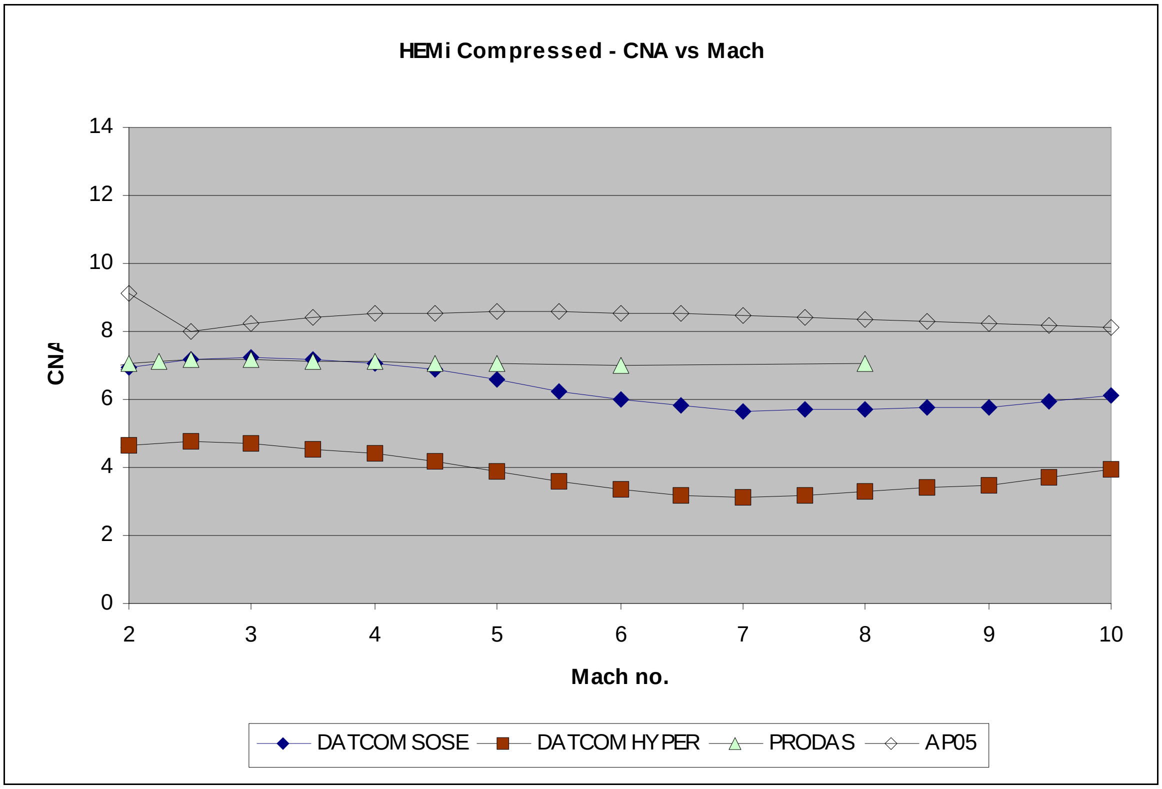


Fig. 24 – HEMi Compressed – CNa vs. Mach

- PRODAS compares well with DATCOM SOSE up to Mach 5.
- There is an important spread of results for this very long dart.

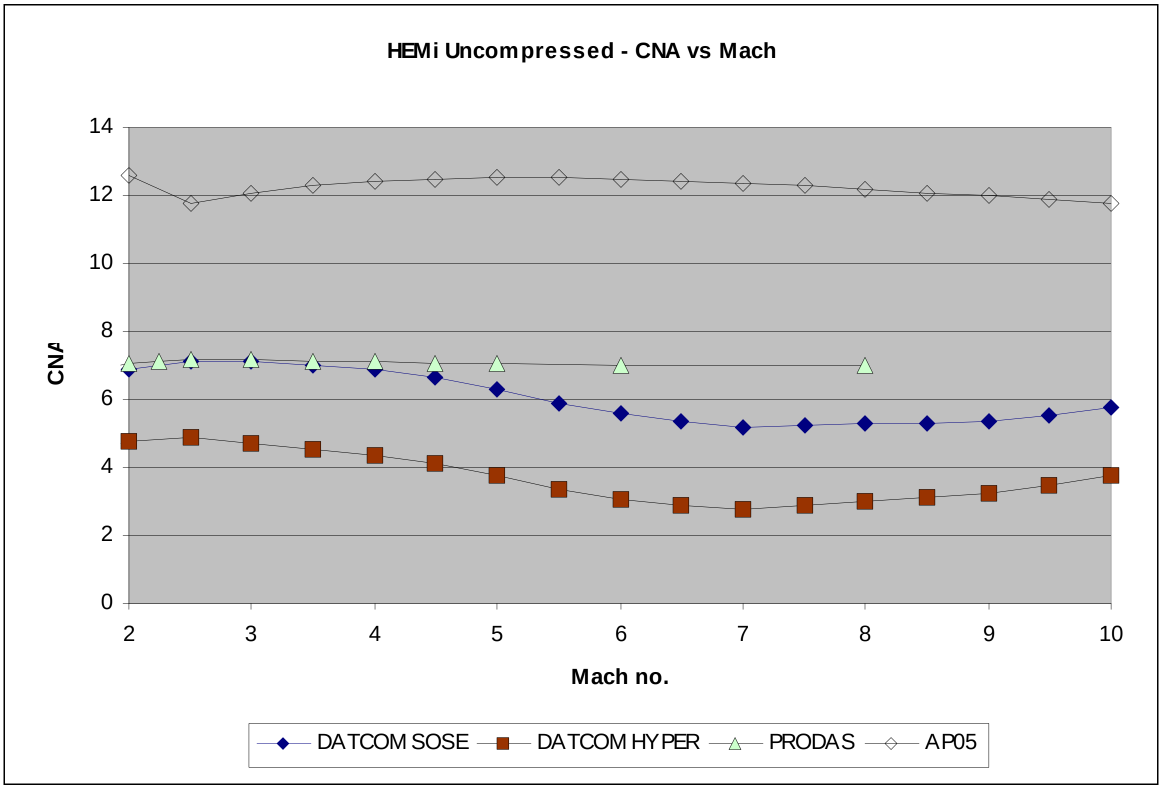


Fig. 25 – HEMi Uncompressed – CNa vs. Mach

- Only AP05 sees an increase in Cna with the increase in projectile length.
- Again, the HEMi configuration is outside of the usual L/D ranges, which might explain the difficulties the codes experience.

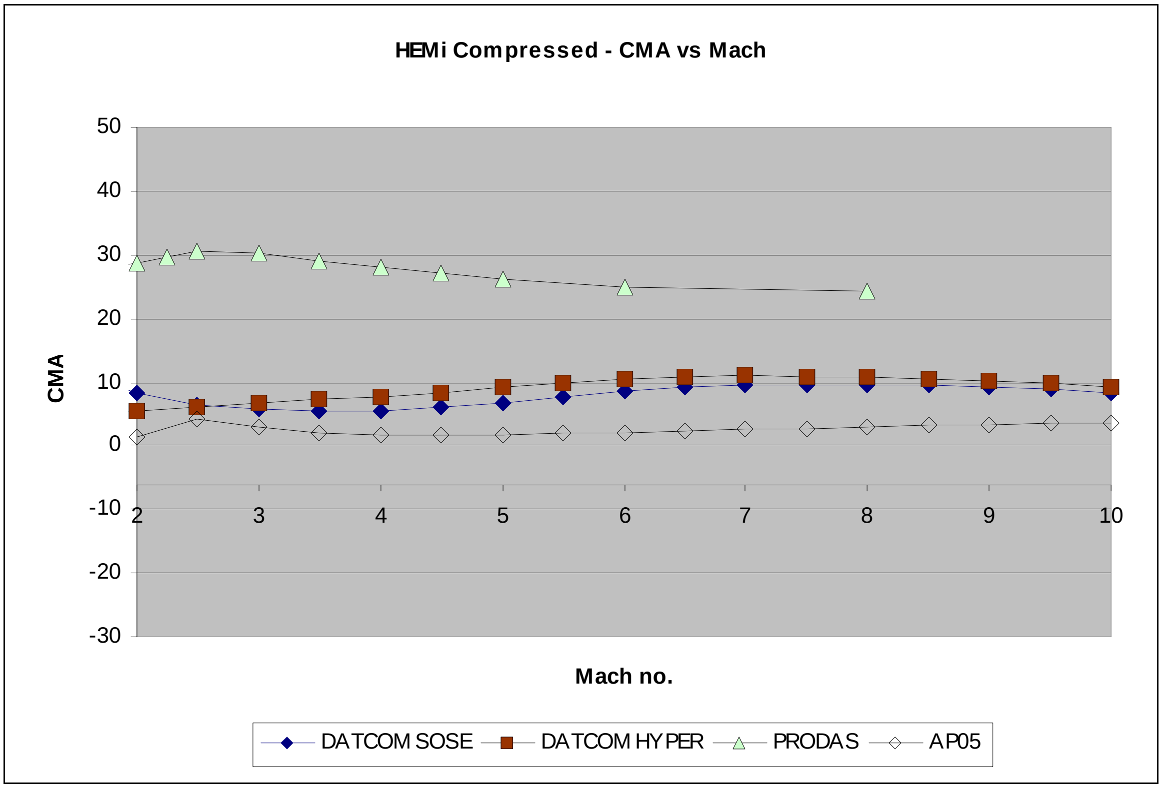


Fig. 26 – HEMi Compressed – CMa vs. Mach

- CMA computed at projectile center of gravity.
- All codes predict an unstable projectile.
- AP05 and DATCOM results follow similar trends

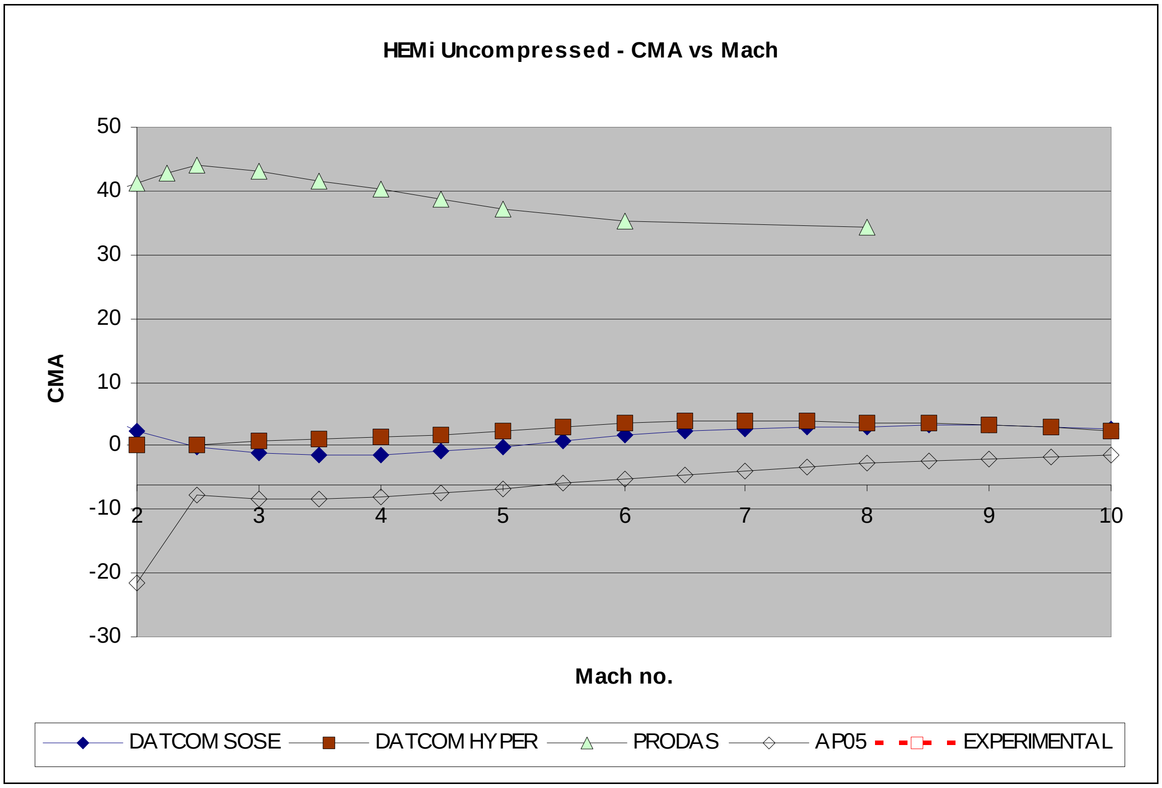


Fig. 27 – HEMi Uncompressed – CMa vs. Mach

- CMA computed at projectile center of gravity.
- With the uncompressed configuration, all codes but Prodas predict an increase in stability. Prodas predicts a loss of stability.
- AP05 predicts a stable projectile until Mach 10.
- DATCOM predicts quasi-neutral stability for the uncompressed configuration.

3.6 RARDE Configuration

3.6.1 Main Aerodynamic Coefficients

Figures 28 to 30 gives the main aerodynamic coefficients for the RARDE projectile. Unfortunately, no test data exists for this projectile.

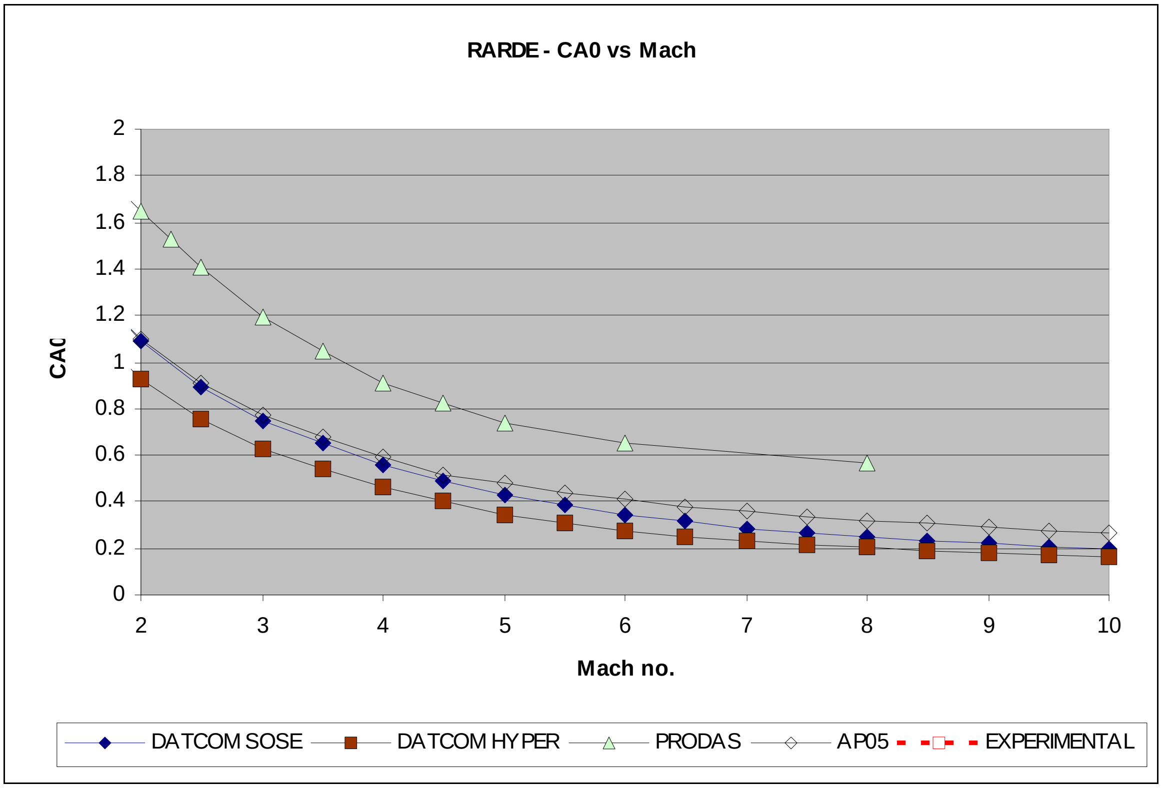


Fig. 28 – RARDE – CA0 vs. Mach

- The small meplat present in the actual RARDE geometry was included in all calculations.
- Base drag component is included in all above data.
- Good agreement between AP05 and DATCOM results.

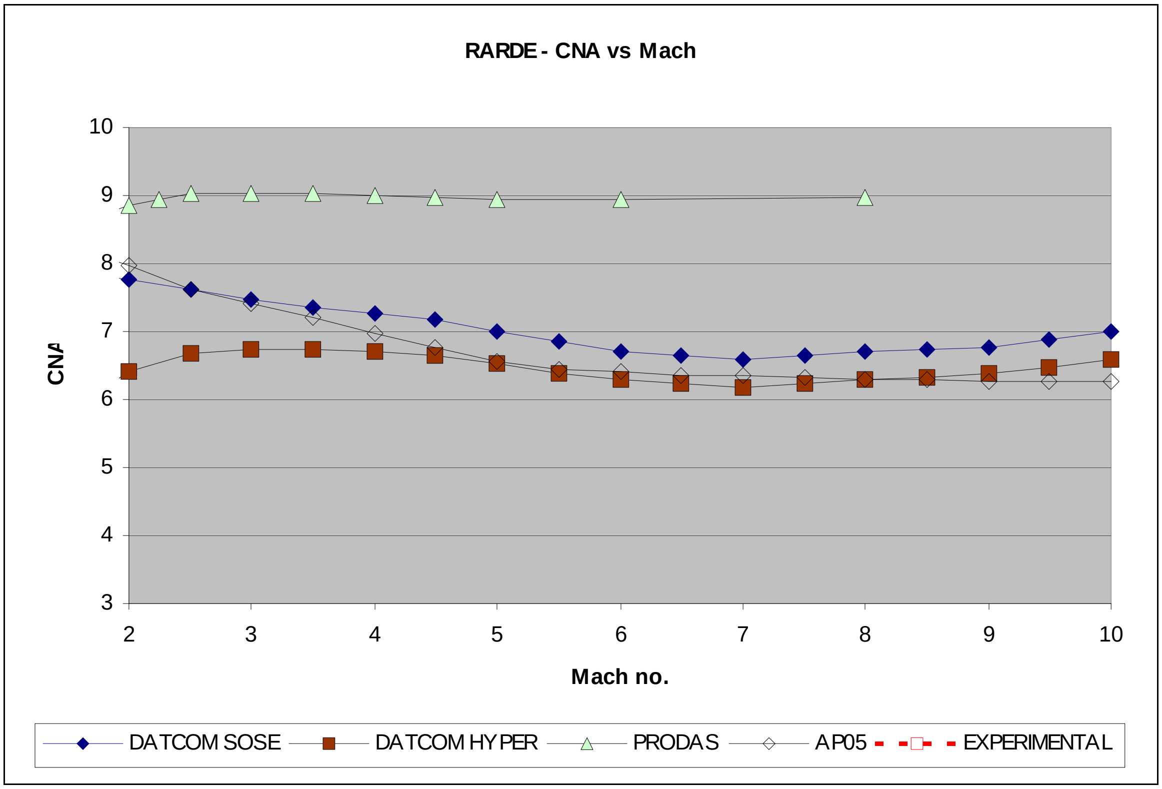


Fig. 29 – RARDE – CNa vs. Mach

- A very good agreement exists between DATCOM and AP05 results for Cna, in both value and trend of the results

- We note that the Newtonian theory reaches the SOSE results around Mach 5 and higher.

- Prodas results are quite higher than the others.

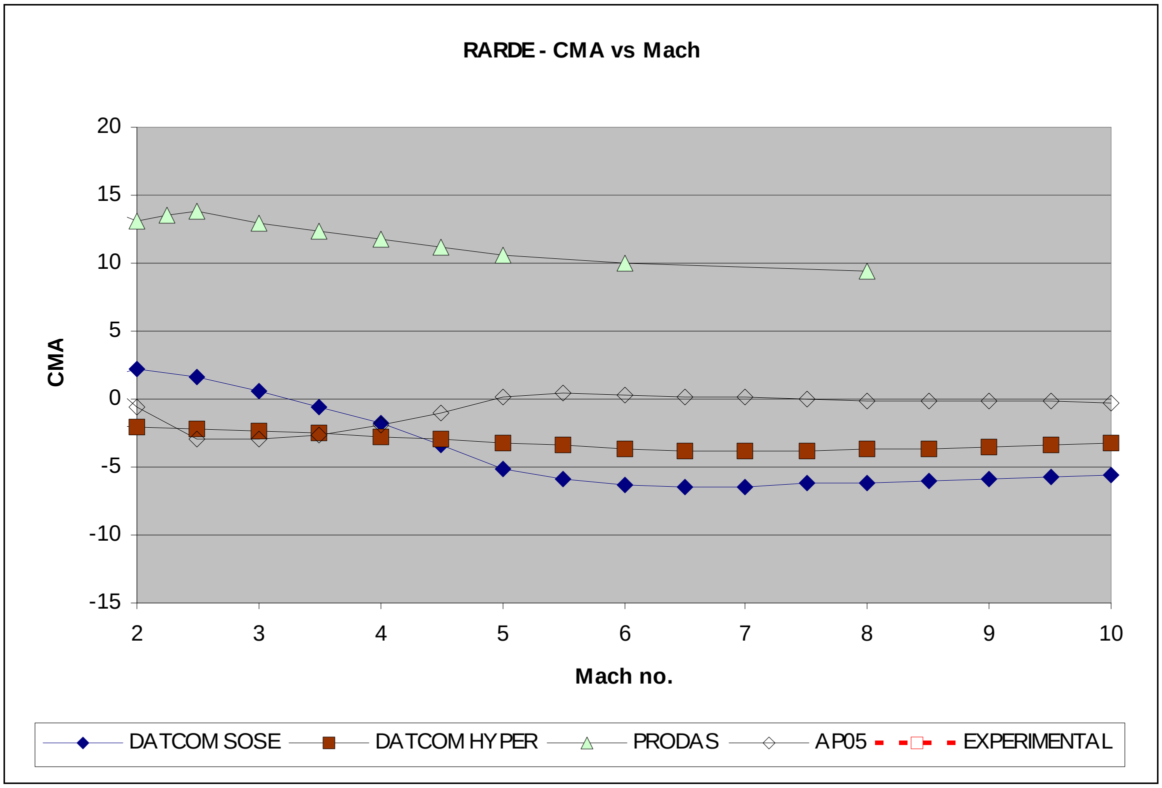


Fig. 30 – RARDE – CMa vs. Mach

- CMA computed at projectile center of gravity.
- PRODAS predicts an unstable projectile
- AP05 predicts stability until Mach 5
- DATCOM predicts stability above Mach 3.3
- This overall discrepancy between predictions is surprising, especially since this model is in the usual geometric parameter ranges.

3.6.2 Pressure distributions

Figures 31 to 34 give pressure distributions on the RARDE projectile, as calculated by Interact, SHEMA, DATCOM and AP05. Figure 31 shows the complete Cp distribution over the length of the projectile as calculated by Interact and SHEMA (Matlab) methods, at Mach 5.2. We note very good agreement over the length of the projectile.

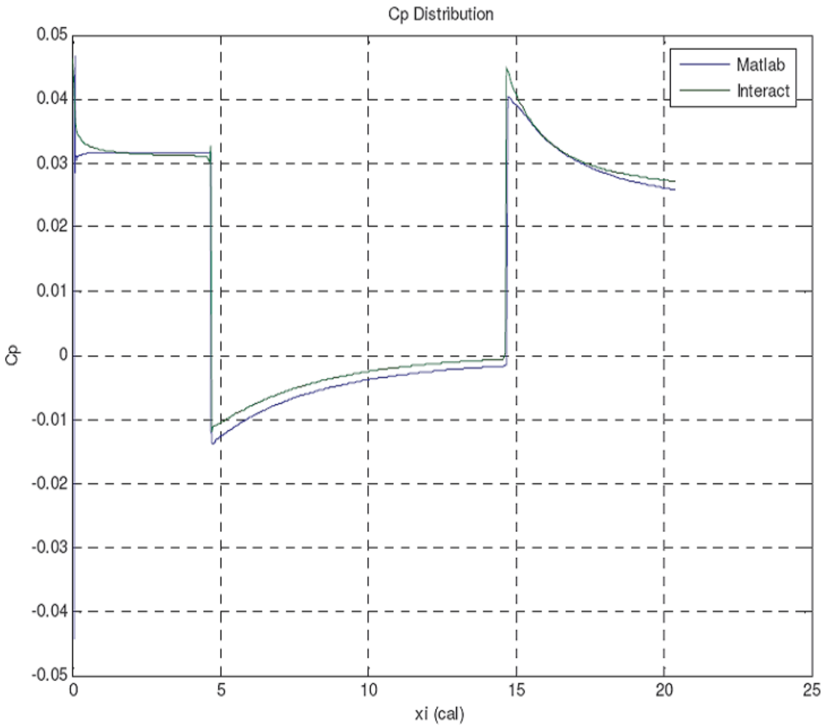


Fig 31 – Pressure Distribution on RARDE configuration - Mach 5.2

Figure 32 compares these previous calculations, at Mach 5.2, with the estimated pressure distribution by AP05 and DATCOM. As noted for the CAN1, AP05 underpredicts the pressure coefficient following the frontal oblique shock. In addition, it does not capture the full expansion effects at the junction of the cone and cylinder, accounting for an instant change of pressure, as should be the case in shock-expansion theory. Finally, the last shock, over the final flare is captured nicely by all methods. This is probably due to the fact that the flare angle is quite small, compared to the CAN1.

As for DATCOM, a bizarre behavior is observed after the frontal shock with some oscillations in the pressure coefficient. This is only seen in the second-order shock-expansion results, whereas the modified Newtonian results follow constant trends. No explanation was found for this behavior.

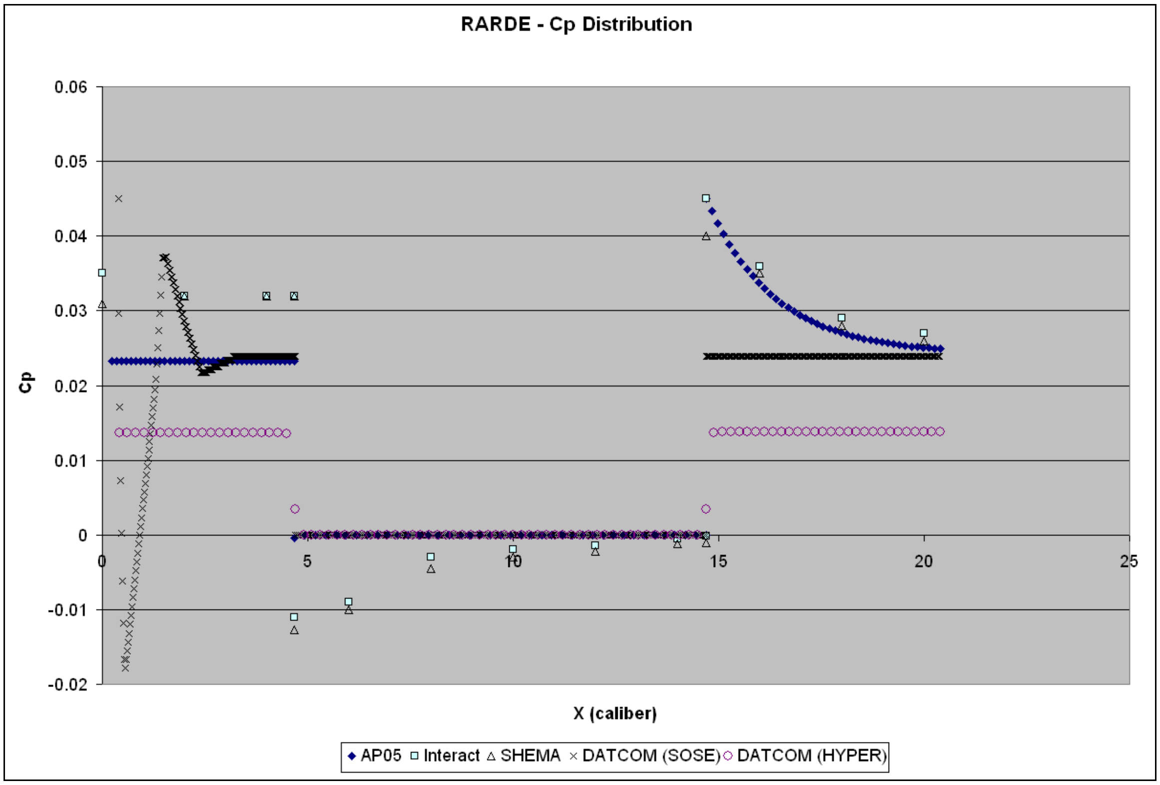


Fig 32 – Code Comparison - RARDE configuration at Mach 5.2

The same comparisons were made at Mach 8.0, as shown in figures 33 and 34. We note a small discrepancy between Interact and SHEMA at this higher Mach number, especially in predicting pressures after shockwaves. The pressure distribution behind the expansion is the same for both methods.

Comparing with AP05 brings to the same conclusions : the pressure rise behind the frontal shock is underpredicted with AP05 and DATCOM, ii) the expansion is calculated instantaneously in AP05, iii) the region behind the last shock is well predicted.

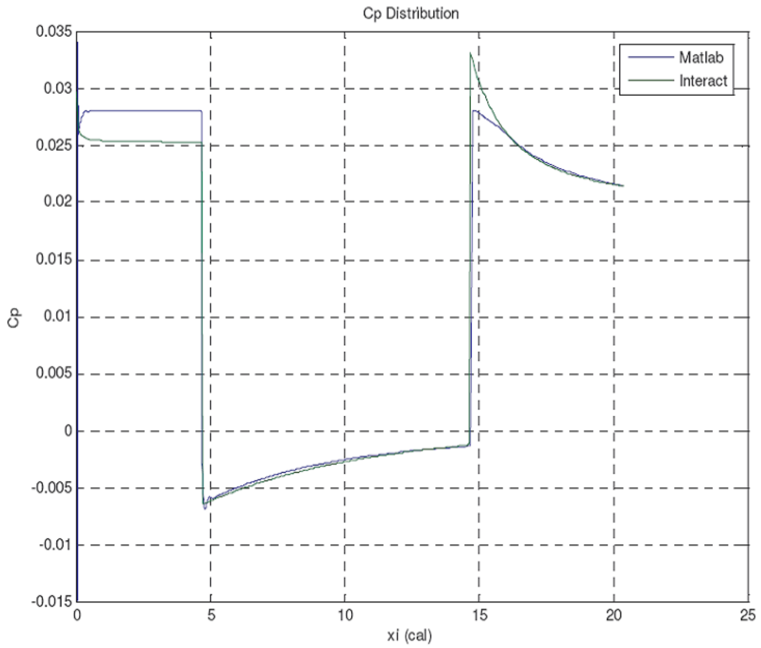


Fig 33 – Pressure Distribution on RARDE configuration - Mach 8.0

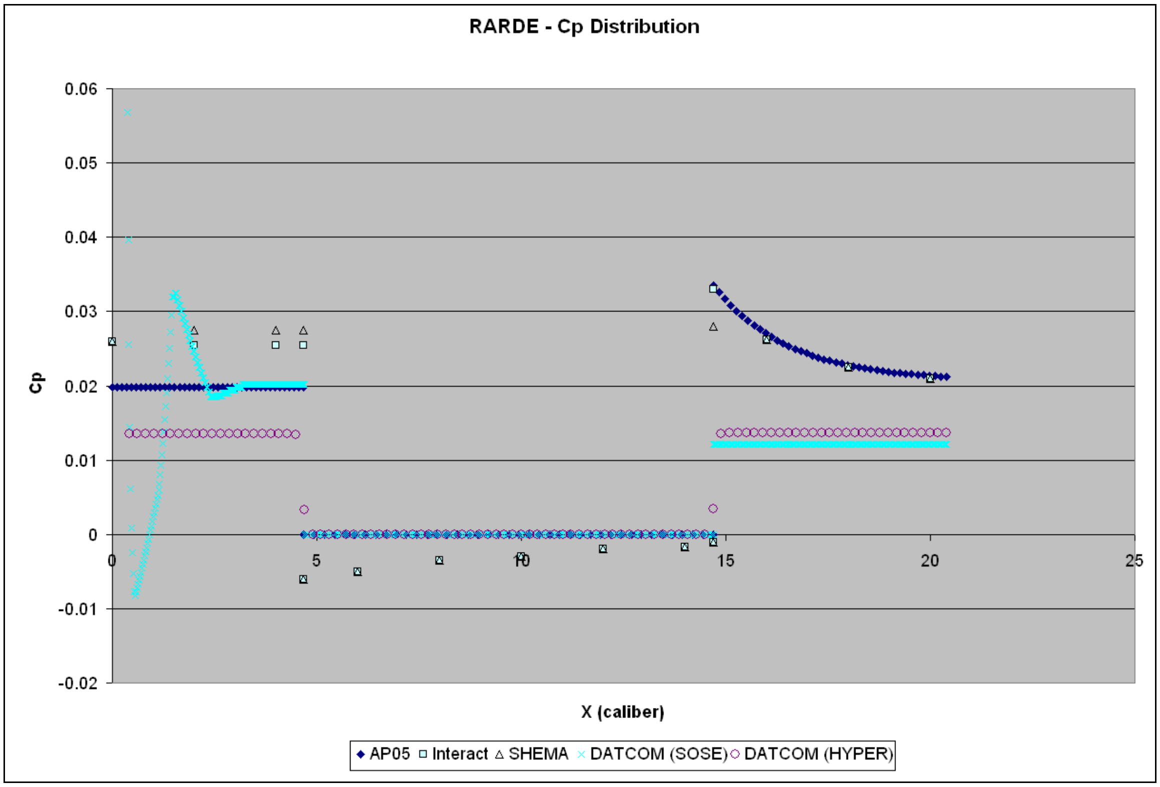


Fig 34 – Code Comparison - RARDE configuration at Mach 8.0

4. Conclusions & Recommendations

- Generally, AP05 and DATCOM aerodynamic coefficients and trends are closer to the experimental data used in this project than other methods. SOSE methods gave a better overall trend in predictions.

- PRODAS seems less accurate than the other codes for high supersonic – hypersonic flows, in all the cases evaluated here. This is possibly due to lack of experimental in the databases for high supersonic – hypersonic fin-stabilized configurations tested in this report.

- The DATCOM Hyper method was more accurate than PRODAS, but not as consistent as the SOSE methods.

- Modified Newtonian theory performs well for configurations with small flow deviation angles (CAN4, HB2). We can expect that the same will hold true for the HEMi configurations. As a general guideline, it is recommended to use these methods for configurations with small flow deviations. This holds true for most of the aerodynamic coefficients obtained in this report.

- When the geometric angles are more pronounced, or fins are present (i.e. CAN1 & CAN3), the SOSE methods are closer to experimental data. It is recommended to use shock-expansion methods for this type of configuration to maximize aerodynamic coefficient accuracy.

- Drag predictions were quite accurate when using DATCOM & AP05. The data shown in this report is for total drag coefficient, including base drag effects.

- Another general guideline is that SOSE methods will perform well up to a certain transition Mach number (generally Mach 6), then the experimental data generally tends towards the modified Newtonian results. However, it was shown that the flow deviation angle criteria listed above has more importance on the results.

- AP05 and DATCOM shock-expansion methods give somewhat different results, depending on the configuration. This is because both methods have different ways of treating the pressure distribution and transforming it in aerodynamic coefficients. This is the semi-empirical part of these codes that appears. The pressure distribution graphs clearly show this offset in pressure prediction.

- Cma results were quite uneven from one configuration to another. This is thought to be caused by possible offsets in the way nose curvature is treated. This can have a very large influence on Cma results. Nose geometries were reproduced as best as possible in the various software utilized.

- SHEMA and Interact give good, accurate, pressure distributions. However, comparing to DATCOM and AP05 pressure distributions clearly illustrates that theoretical methods bring a certain uncertainty in the calculations, especially near the shocks and expansions present on the configurations.

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Annex 1 – Example of Input Files & Results

All input files & results are included in a CD, sent with this report.

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1. ORIGINATOR (name and address) DRDC Valcartier 2459 Pie-XI Blvd North Québec, Québec, G3J 1X5	2. SECURITY CLASSIFICATION (Including special warning terms if applicable)

3. TITLE (Its classification should be indicated by the appropriate abbreviation (S, C, R or U)

Evaluation of Aerodynamic Software in the Hypersonic Flow Regime (U)

4. AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

Nicolas Parisé

5. DATE OF PUBLICATION (month and year) August 2007	6a. NO. OF PAGES 40	6b .NO. OF REFERENCES 8

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. Give the inclusive dates when a specific reporting period is covered.)

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8. SPONSORING ACTIVITY (name and address)

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9a. PROJECT OR GRANT NO. (Please specify whether project or grant) 13eu02	9b. CONTRACT NO. W7701-053774/001/BAL
10a. ORIGINATOR'S DOCUMENT NUMBER DRDC Valcartier CR 2007-247	10b. OTHER DOCUMENT NOS N/A

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The goal of the current project is to evaluate the accuracy of aero prediction tools in predicting main aerodynamic coefficients in the range between Mach 3 and 8. To achieve this, seven flight configurations, which have been tested experimentally, are used in a comparative study. The main aeroprediction codes used for this study are Prodas V3, Datcom, AP05. They are compared between Mach 3 and 8, and focus is made on accuracy in predicting major aerodynamic coefficients : Cx, Cna and Cma. In addition to these codes, results from SHEMA and Interact are used to illustrate the relative accuracy on predicted pressure distribution on the configurations..

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