PANAIR APPLICATIONS TO STORE SEPARATION (*déjà vu again*)

A. Cenko*, AIWS LLC
Huntingdon Valley, PA USA

ABSTRACT

During the last five decades, Computational Fluid Dynamics (CFD) has been increasingly integrated into the store separation process. Starting with linear theory (panel methods), small disturbance, full potential, Euler and finally Navies Stokes (NS) solutions, CFD predicted trajectories have become more acceptable as a supplement/replacement to wind tunnel testing. Now, the major question in using CFD has become whether Euler code solutions are sufficient or NS must be used. This paper describes how panel methods might still be the best application for certain store separation conditions.

Nomenclature

A_i	Normal Force Influence Coefficient
B_i	Pitching Moment Influence Coefficient
C_i	Side Force Influence Coefficient
D_i	Yawing Moment Influence Coefficient
BL	Aircraft Buttline, positive outboard, inches
CFD	Computational Fluid Dynamics
CTS	Captive Trajectory System
C_A	Axial Force Coefficient, positive aft
C_N	Normal Force Coefficient, positive up
C_Y	Side Force Coefficient, positive right wing
C_l	Rolling moment coefficient, positive right wing down
C_m	Pitching moment coefficient, positive nose up
C_n	Yawing moment coefficient, positive nose right
IFM	Influence Function Method
M	Mach number
N	Number of Store Segments
P	Store roll rate, positive right wing down, degrees/second
Q	Store pitch rate, positive nose up, degrees/second
R	Store yaw rate, positive nose right, degrees/second
PHI	Store roll angle, positive right wing down, degrees
PSI	Store yaw angle, positive nose right, degrees
THE	Store pitch angle, positive nose up, degrees
WL	Aircraft Waterline, positive up, inches
α	Angle of attack, degrees
α_i	Upwash angle of segment i, positive up, degrees
ε	Upwash angle, positive up, degrees
δ_i	Sidewash angle of segment i, positive outboard, degrees
σ	Sidewash angle, positive outboard, degrees

INTRODUCTION

In the early days, store separation was conducted in a hit or miss fashion - stores would be dropped from the aircraft at gradually increasing speeds until the store came closer to or sometimes actually hit the aircraft. In some cases, this led to loss of aircraft, and made test pilots reluctant to participate in store separation flight test programs.

During the 1960’s, the Captive Trajectory System (CTS) method [Bamber, 1960] for store separation wind tunnel testing was developed. The CTS provided a considerable improvement

*CEO, Associate Fellow AIAA, Email cenkoa@gmail.com

over the hit or miss method, and became widely used in aircraft/store integration programs prior to flight testing. However, CTS was not utilized in an integrated approach, since the group conducting the wind tunnel test was generally separated both in organization and location from those responsible for conducting the flight test program and determining the safe separation envelope. Furthermore, since small scale models had to be used in the wind tunnel tests, in many cases the wind tunnel predictions did not match the flight test results. No mechanism was then in place to resolve the wind tunnel/flight test discrepancies.

Since the time Computational Fluid Dynamics (CFD) was first capable of representing the geometric complexity of an attack aircraft with external stores [Rogers, 1976], there has been the desire to replace/reduce the need for wind tunnel testing. The three detriments for full utilization of CFD in this fashion were computational speed, computer resources and accuracy of the solution. For the Advanced Weapons Carriage and Separation (AWCAS) configuration shown in Figure 1, one solution using a linear code with 1000 panels required full utilization of the supercomputer of that time (CDC 6600) for twenty-four hours [Cenko, 1979]. Clearly, the wind tunnel was in no danger. As a metric of where we are now, the same solution will now run in seconds on a PC.

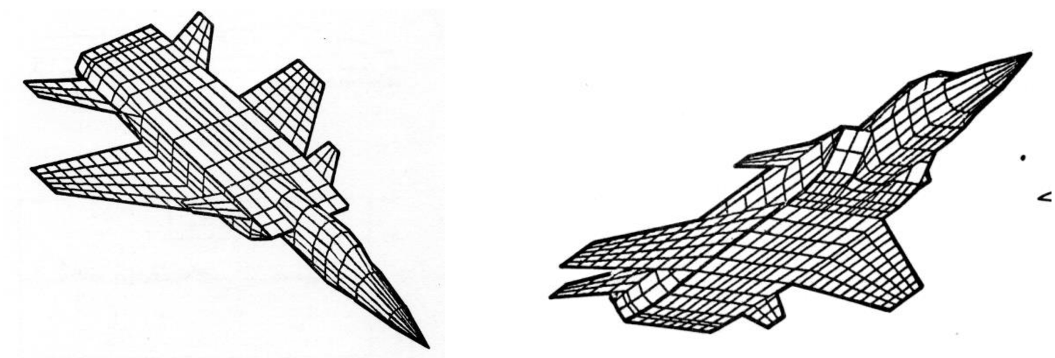

Figure 1 PAN AIR Panelling for the AWCAS Configuration

For this reason, the first step in separation analysis is to estimate the region of the flight envelope that might have the worst carriage moments. This is done by deriving an estimate of the aircraft effects at the store location. Prior to the development of the Chimera technique [Steger, 1983] the only tools to evaluate the aircraft/store aerodynamics were wind tunnel or linear theory.

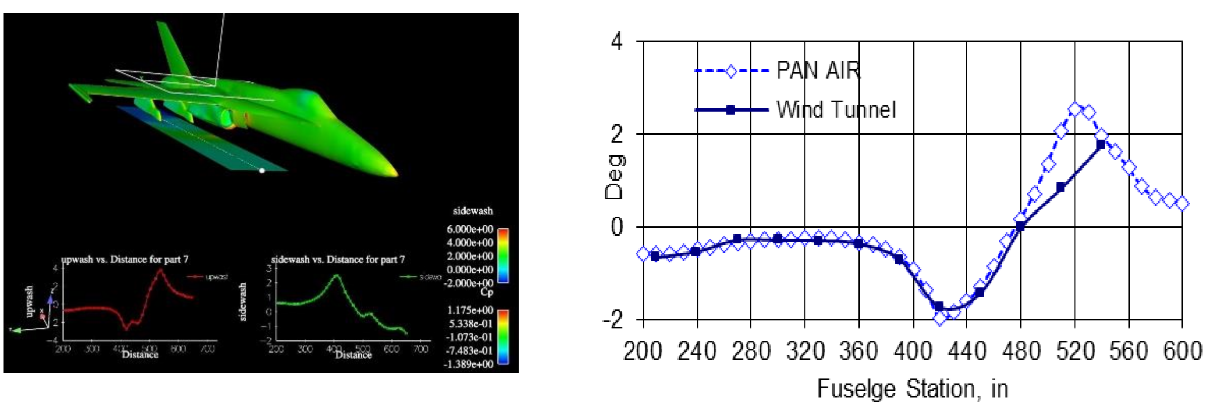

Figure 2. Aircraft Upwash and Sidewash effects

Although potential flow codes had demonstrated the ability to predict complex aircraft flowfields in the linear speed regime, yaw head probe flowfield test data, Figure 2, were used to validate the analytical aircraft models. In the US, the yaw head probe test data were usually acquired at the DTRC 7x10, AEDC 4x4 and the CALSPAN 8x8 foot transonic wind tunnels.

Due to the large time required for one computation, a technique that could use the clean aircraft flowfield was developed at Grumman under an Air Force contract. The Influence Function Method (IFM) [Meyer,1981, Keen 1985, Cenko, 1986] was used to determine the effect of the aircraft flowfield on the store loads and moments.

Using the aircraft flowfield and store influence coefficients, an estimate of store aerodynamic coefficients was made everywhere in the flowfield, including carriage. The store aerodynamic coefficients were then input in a Six-Degree-of-Freedom (SDoF) program to simulate the store's trajectory prior to the wind tunnel test. The simulated trajectories were used to help design the wind tunnel test to ensure that the most critical regions of the store separation envelope were tested. This approach was the principal technique for inserting computational aerodynamics in the flight clearance process during the 1980's, and its derivative (FLIPTGP) is still used by the air force.

Starting in the late 1980’s the US Air Force and Navy tried to validate and accelerate the insertion of CFD methods into the store certification process. There have been several organized international conferences for this purpose.

The first of these was for the Wing/Pylon/Finned-Store, which occurred in Hilton Head, SC in the summer of 1992. One of the important results from this initial conference was the discovery that full potential methods [Newman, 1992, Madson, 1994] gave answers equivalent to those provided by a Euler code for the wing lower surface in the presence of the store.

The second conference was sponsored by the Office of the Secretary of Defence funded Applied Computational Fluid Dynamics (ACFD) program. This was for the F-16/Generic Finned Store, also called ACFD Challenge I; the conference took place in New Orleans in the summer of 1996 [Madson, 1996].

Starting in early 2000, after ACFD Challenge II [Cenko, 2002], CFD became a regular tool in the store separation process for external stores.

DISCUSSION

The Wing/Pylon/Finned-Store Configuration was the first attempt to validate CFD predictions for store separation. Although not allowed to compete in this challenge (panel methods are not CFD [Belk, 1992]), it was later shown [Madson, 1994, 1996] that full potential solutions were equivalent to those using Euler codes. The NS solutions exhibited the best correlation in shock location, but were not superior to the full potential or Euler results. Since then, two other CFD Challenges [Madson,1996, Cenko, 2002] have not demonstrated any advantage in the ability of NS solutions to predict store trajectories over those of full potential or Euler codes [Demir, 2016].

One possibility for this is that the CFD challenges were conducted for Mach numbers in the transonic regime where the shock wave is close to normal, and the Euler solution gives the most conservative answer, which is best for flight clearance purposes.

Due to Moors law panel methods have lost favour in store separation applications. Since solutions for one aircraft store trajectory can now be done in hours, instead of days or weeks, the time for each calculation is no longer as critical.

There might be cases where panel methods might still be useful.

Search and Rescue (SAR) Store Separation from Turbojet Aircraft.

The Australian Maritime Safety Authority (AMSA) is replacing Dornier 328 turboprops with Bombardier Challenger 604 special mission jets modified for search and rescue (SAR). Similarly configured CL-604 Multi-Mission Aircraft are in service with the Royal Danish Air Force.

There are several store separation challenges posed by replacing a turboprop aircraft with a turbojet. For the 328 the rear cargo door used for store separation is well clear of the engine. For the 604 it's just underneath the nacelle. In addition, the minimal airspeed at which the 604 can release stores is higher.

Unlike military aircraft, Sea Air Rescue has not used wind tunnel testing, Computational Fluid Dynamics (CFD) nor Six Degree-of-Freedom (SDOF) trajectory simulations prior to flight testing. This might have been since the released stores were relatively light weight, the airspeeds low, and incidental contact with the aircraft unlikely to cause significant damage at low airspeeds.

This paper will describe how SDOF trajectory simulations might be used to reduce the cost and time required to safely complete a turbojet SAR flight test program.

Requirements for store trajectory Simulation

Geometry

The first step in trajectory simulations is to obtain the aircraft and store geometries.

A representative 604 geometry was obtained from the internet. This geometry had to be scaled to fit the published 604 aircraft dimensions.

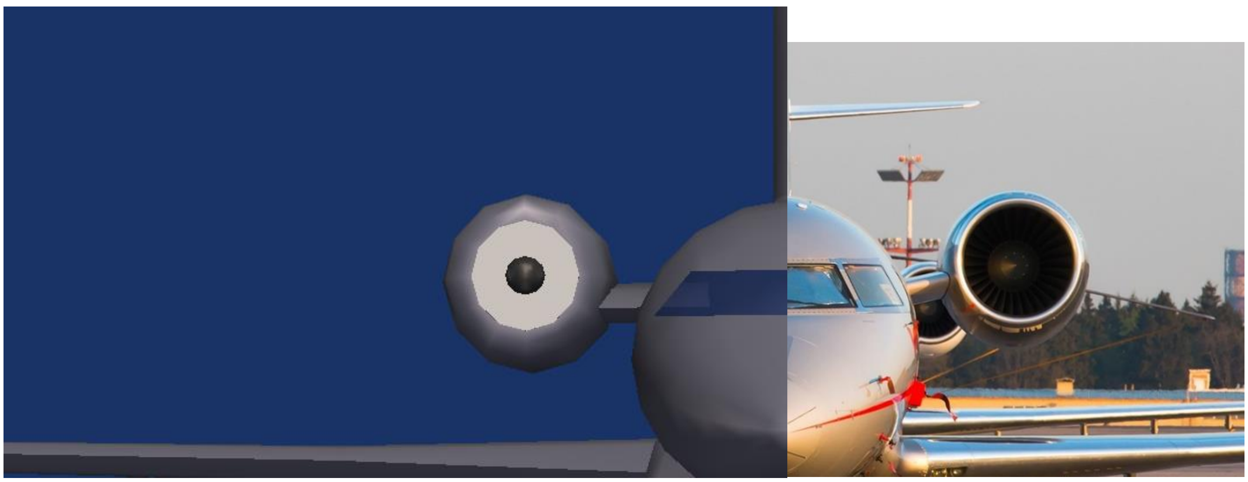

Figure 3 Comparisons of the 604-geometry model and picture of the aircraft

As may be seen in Figure 3, the 604 model, while not exact, represents the critical features of interest for the trajectory simulations. These are the relative locations of the fuselage, nacelles and wing.

Freestream

The next step is acquiring the freestream aerodynamic characteristics for the stores. These are generally obtained from wind tunnel testing.

For SAR, which uses cylindrical and rectangular shapes, no representative data were available, since wind tunnel freestream data is usually taken only to 40-60 degrees. Lack of freestream data might account for no known SDOF simulations in previous SAR store release programs.

DATCOM estimates were used to generate a set of aerodynamic coefficients from 0 to 360 degrees. The most important coefficients are C_N and C_m, and not representative of what the stores might do.

This was done only to provide input to the SDOF code.

Initial Conditions

Since a SDOF code predicts a store's trajectory with time, any error in the initial conditions will be compounded as the trajectory proceeds. The usual deployment for stores for SAR involves a loadmaster, which insures that the initial conditions are variable to some extent, and not repeatable. This might also account for no SDOF simulations in previous SAR store release programs

<u>Aircraft Flowfield</u>

Next to store freestream effects and initial conditions the most important impact on store trajectories is the aircraft flowfield. For military aircraft, this is of critical importance, and has caused many cases of aircraft damage, and sometimes loss of the aircraft in the early days of store separation, when flight testing was conducted in a hit or miss fashion. The aircraft flowfield effects increase with the square of the release airspeed.

Panel Methods can accurately predict aircraft flowfield effects. Combined with an approach that estimates the store loads based on the aircraft flowfields hundreds of trajectory simulations could be done in minutes.

Influence Function Method

The IFM [Meyer,1981, Keen 1985, Cenko, 1986] technique assumes that there is a direct relationship between the aircraft flow field along a store and the forces and moments induced by the aircraft flow field on the store. Conceptually, for a store broken into N segments, this is expressed by the relationship:

C_N =□□ A_i*□$_i$, i=1,N

C_m =□□ B_i*□$_i$, i=1,N

C_Y =□□ C_i*□$_i$, i=1,N

C_n =□□ D_i*□$_i$, i=1,N

The first step in the IFM process is calibration, i.e., determining the store's Influence Coefficients A_i and B_i, which determine its response to the aircraft flow field. For symmetric stores, C_i and D_i are identical to A_i and B_i. It must be emphasized that a store's Influence Coefficients are not an aerodynamic property, but rather a solution to a regression equation relating a series of store aerodynamic loads to a known aircraft flow field.

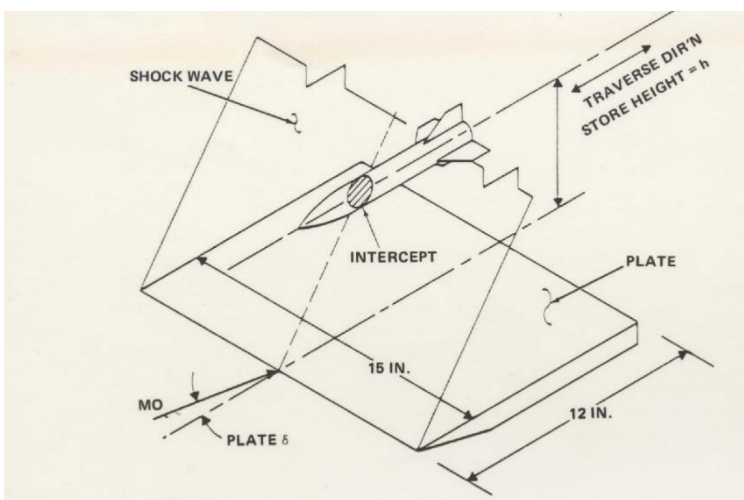

Figure 4 Wind Tunnel Test for IFM Calibration

Originally, these influence coefficients were experimentally determined as shown in Figure 4. For each store position the store aerodynamic coefficients and local angle of attack α_i were known. The store influence coefficients were then determined by inverting the matrix to solve for the unknown influence coefficients.

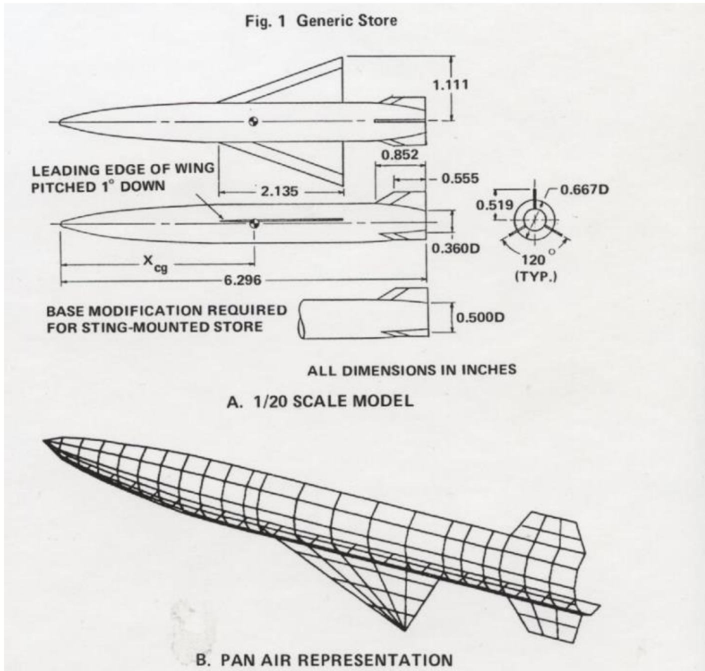

Figure 5 PanAir Representation of Wing Body Store (WBS)

It was later shown that the PanAir code could accurately predict the WBS (shown in Figure 5) CN and C_m reaction to the shock wave in the wind tunnel, Figure 6.

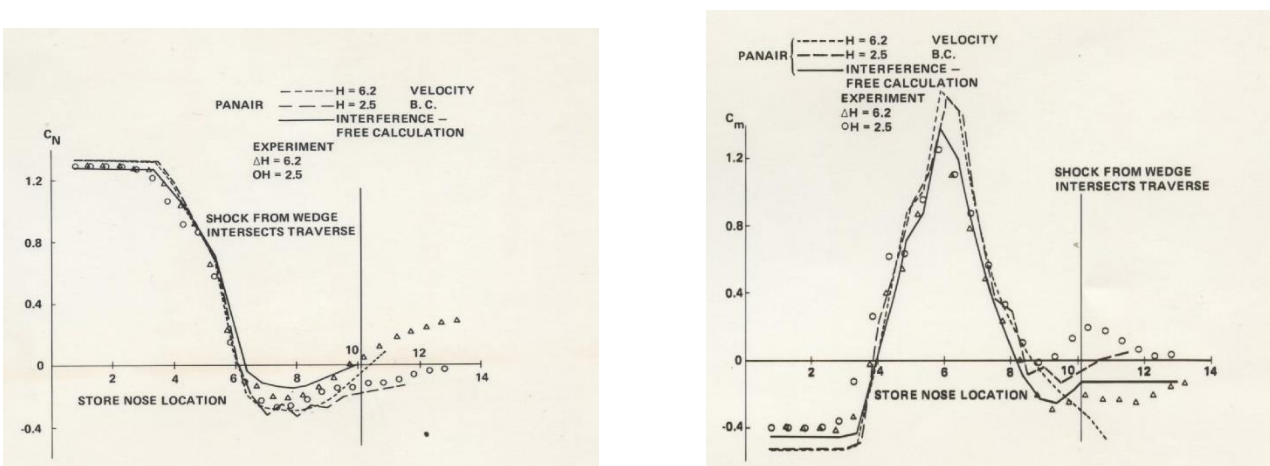

Figure 6 PanAir Predictions of WBS Forces and Moments

The second step in the IFM process is the determination of the aircraft flow field. Originally, this was done experimentally; however, with the advent of linear tools that could handle arbitrary aircraft/store geometries, aircraft flow fields were determined analytically [Cenko, 1984].

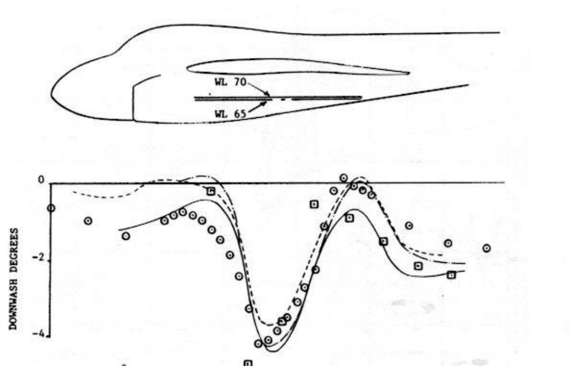

Figure 7 PanAir Predictions of A-6E Aircraft Flowfield

As may be seen in Figure 7, PanAir can accurately predict the aircraft flowfields at two different aircraft waterlines.

Using the aircraft flow field and store influence coefficients, an estimate of store aerodynamic coefficients can be made everywhere in the flowfield in one calculation. This process was called **C**ost **R**educing **A**pplications to **P**anAir.

The store aerodynamic coefficients are then input into a six-degree-of-freedom program to simulate the store's trajectory.

The IFM technique was improved by Keen, and incorporated into the AEDC Flow-Angle Trajectory Generation Program (Flow TGP) [Keen, 1990]. Interestingly, similar approaches were independently developed in Great Britain (NUFA) [Bizon,1985] and Australia (DSTORES) [Fairlie, 1999].

RECOMMENDED SAR PROCEDURE

Freestream

Pan Air calculations were made for the store freestream aerodynamic characteristics for various store shapes [Aykroyd, 2017]. Comparisons for cylinders of two different shapes are shown with DES [Prosser, 2015] calculations in Figures 8 and 9.

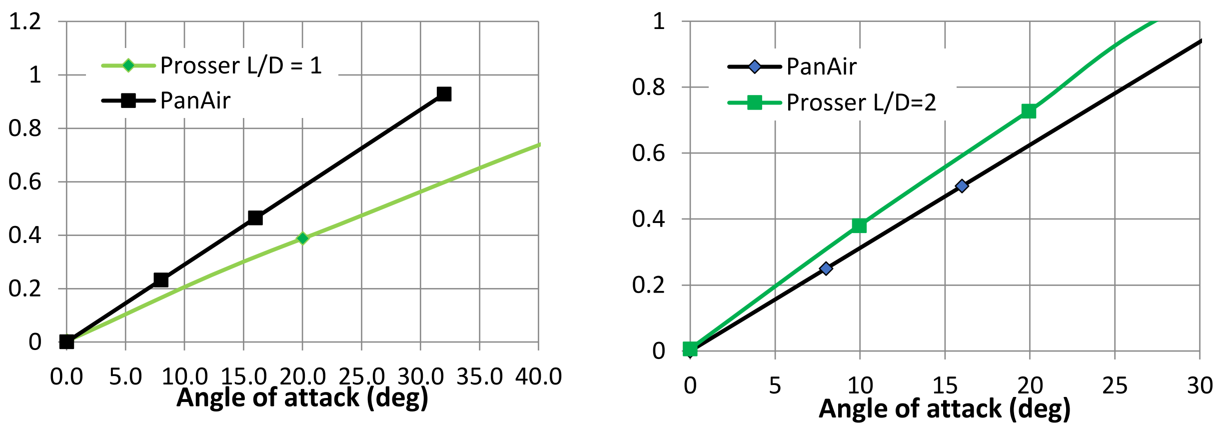

Figure 8 Normal Force Comparisons for Circular Cylinders

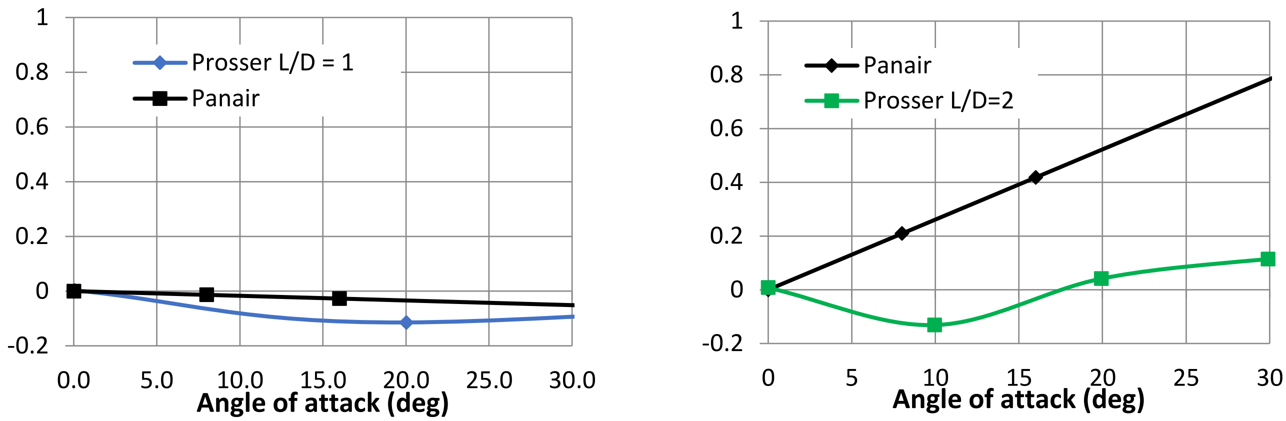

Figure 9 Pitching Moment Comparisons for Circular Cylinders

The comparisons for the pitching moments are in poor agreement, but they do indicate the tendency for the cylinders to become unstable with increasing L/D rations.

Aircraft Flowfield

The aircraft geometry can be obtained from the internet. A crude PanAir representation should give a reasonable estimate of the Upwash and Sidewash at all aircraft BL and WL locations of interest.

Flap Effects

Flap effects could be easily modelled [Moyer, 1993] by using boundary conditions. As may be seen in Figure 10, PanAir gives an excellent match to the lower surface wing pressures using both physical deflections and mass flux boundary conditions.

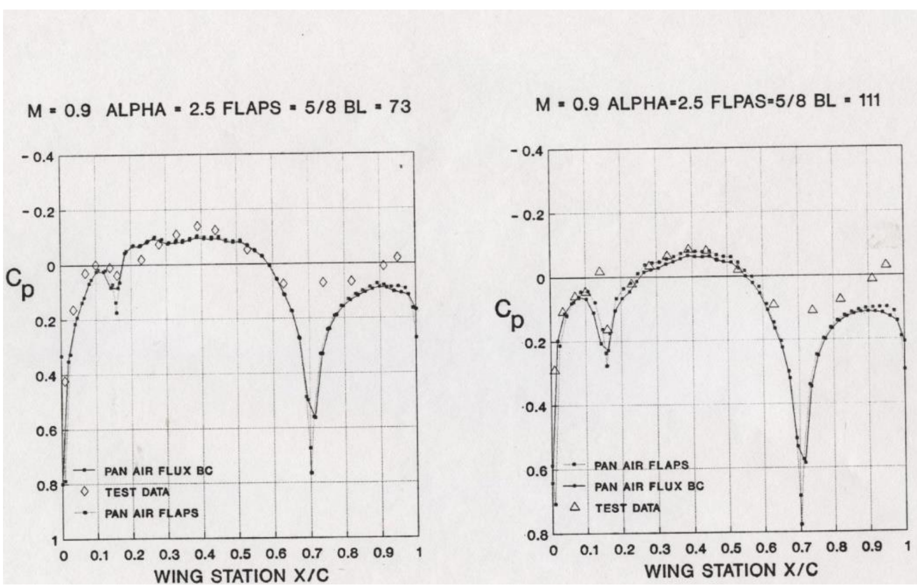

Figure 10 PanAir Prediction of Wing Pressure Changes due to Flaps

Trajectory Simulation

One example of how the IFM technique could be used to provide grid data underneath the aircraft was the BQM-126A separating from the F-18C Aircraft.

The BQM-126A, shown in Figure 11, was a powered UAV designed to be carried on the F-18C/D aircraft. CTS testing was performed in the DTRC 7x10 tunnel [Popham, 1987] to determine safe separation.

Figure 11 BQM-126A

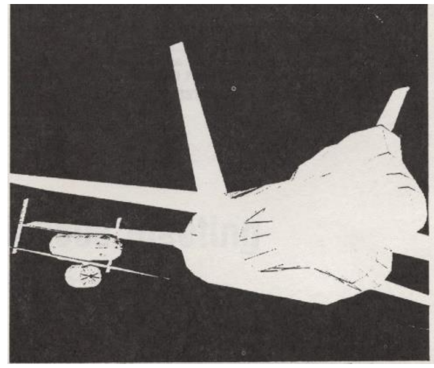

Figure 12 PanAir Model of F-18C/BQM-126A

The wind tunnel tested only CTS trajectories. No grid testing was done. No off-line trajectory simulations were performed prior to flight testing.

The CTS simulation indicated that the store would move aft and safely clear the aircraft. The wind tunnel CTS trajectories simulated three different levels of trust for the engine, with no change in trajectories. In the first flight, the store flew forward and almost hit the F-18C aircraft.

The IFM code was used to calibrate the BQM-126A geometry [Cenko, 1987] and predict the F-18 aircraft Flowfield. The analysis matched the flight conditions [Cenko, 1990], and no further F-18/BQM-126A flight test were conducted.

“This target missile first flew in 1984. Although the U.S. Navy planned to order 700 units, the entire project was eventually cancelled and never went into production. On display in Hangar 3 at the Yanks Air Museum, Chino, California, USA.”

Note that one PanAir calculation was performed for the store in the carriage position, Figure 12. At that time, the cost in computer time to generate a grid were considered prohibitive.

CONCLUSIONS

Five decades ago panel methods were the only tools other than wind tunnel that could predict store trajectories. With advances in computer speed and computational algorithms, Euler and NS solutions have become the standard. The paper discusses a case where panel methods might still be used.

References

Akroyd, G., et. al. “Store Separation Analyses for Maritime Search and Rescue Jets,” AIAA Forum, June 5, 2017, Denver, CO.

Bamber, M. J., “Two Methods of Obtaining Aircraft Trajectories from Wind Tunnel Investigations,” AERO Report 970 (AD 233198), David Taylor Model Basin, Washington, DC, Jan. 1960.

Belk, D. “private correspondence’ 1992.

Bizon, S. A., NUFA - A technique to Predict the Aerodynamic Characteristics of Store Configuration in a Non-Uniform Flowfield," AGARD CP-389, 1985.

Cenko, A., and Tinoco, E. N., “PAN AIR - Weapons, Carriage and Separation,” AFFDL-TR-79-3142, Dec. 1979.

Cenko, A., et al., “Further Development of the Influence Function Method for Store Aerodynamic Analysis,” J. Aircraft, Vol. 23, August 1986, pp 656-661.

Cenko, A., et al. “IFM Applications to Theoretical Trajectory Predictions,” AIAA Paper 87-0210, Jan. 1987.

Cenko, A., et al. “IFM Applications to Complex Store Configurations,” AIAA Paper 90-0275, Jan. 1990.

Cenko, A., et al., "NADC Approach to Air Launch Certification," AIAA Paper 92-2900, August 1991.

Cenko, A., and Lutton, M., “ACFD Applications to Store Separation – Status Report,” The Aeronautical Journal, Volume 104, Number 1040, Oct 2002.

Demir, G. “Computational Fluid Dynamic Modeling of Store Separation Using the Grid Method,” METU Master’s Thesis, Feb. 2016.

Fairlie, B., and Caldeira, R., “Prediction of JDAM Separation Characteristics from the F/A-18 Aircraft,” AIAA Paper 99-0126, Jan. 1999.

Keen, K. S., “Inexpensive Calibrations for the Influence Function Method Using the Interference Distributed Loads Code,” J. Aircraft, Vol. 22, January 1985, pp 85-87.

Keen, K. S., "New Approaches to Computational Aircraft/Store Weapon Integration," AIAA paper 90-0274, Jan. 1990.

Meyer, R., Cenko, A., and Yaros, S., “An Influence Function Method for Predicting Aerodynamic Characteristics During Weapon Separation,” 12th NAVY Symposium on Aeroballistics, May 1981.

Madson, M. et al “TranAir Computations of the flow about a Generic Wing/Pylon/Finned-Store Configuration,” AIAA paper 94-0155, Jan. 1994.

Madson, M. and M. Talbot, “F-16/Generic Store Carriage Load Predictions at Transonic Mach Numbers using TranAir,” AIAA-96-2454, June 1996.

Moyer, S. A., “PAN AIR Analysis of Simply Connected Control Surface Deflections,” Journal of Aircraft, Vol. 1, Jan-Feb 1983, pp. 154-156.

Newman, J.C. and Baysal, O. "Transonic Solutions of a Wing/Pylon/Finned Store Using Hybrid Domain Decomposition, AIAA paper 92-4571, Aug. 1992.

Popham, E. R., “F/A-18 Aircraft/BQM -126A Target Drone Separation/Jettison Characteristics Report,” MDC Report No. BO377, May 1987.

Prosser, D., and Smith, M., “Aerodynamics of Finite Cylinders in Quasi-Steady Flow,” AIAA paper 2015-1931, Jan. 2015.

Rogers, R., M., “A Comparison Between the Nielson and Woodward Programs in Predicting Flow Fields and Store Loads,” Naval Weapons Center TM 2854, July 1976.

Steger, J. L., Dougherty, F. C., and Benek, J. A., “A Chimera Grid Scheme,” Advances in Grid Generation, ASME, June 1983.