# 30 Years of CFD: Its Evolution During the Career of Pierre Perrier

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It is an honor to be invited to provide an article for the volume celebrating the contributions of Pierre Perrier to aeronautical science. These have been widespread, ranging from his central role in the design of a series of remarkable aircraft (Figure 1,2,3,4), thorough the development of both analytical and computational methods in aerodynamics, and beyond to history and philosophy. The breadth of his interest and perspective are a strik-

Figure 1: Mirage 2000/4000

Figure 2: Rafale

Figure 3: Falcon 100

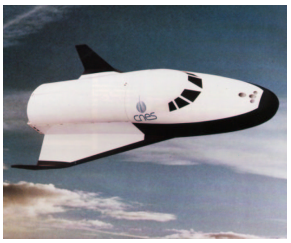

Figure 4: Hermes Spacecraft

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ing feature of his unique career, which has had such a major impact on the development of aeronautical science.

In this contribution I focus on the evolution of computational fluid dynamics during the last three decades, which span rather precisely the career of Pierre Perrier. In fact this science barely existed at the start of his career. By now it is fairly mature and provides the foundation of the aerodynamic design process in both the preliminary and detailed design phases. Pierre Perrier has had a significant role in bringing this about both through his insistence on the need for methods that could treat general configurations and complex flows, and his persistence in forcing the development of such methods.

Here I will illustrate the progress with some examples drawn from my own work since 1970. At that time we had no computational capability in fluid dynamics at all at Grumman Aerospace, where I was working, although Hess and Smith had announced their panel method several years earlier. In order to get started I wrote two computer programs for two dimensional ideal potential flow, flo1 and syn1, both based on conformal mapping. Flo1 calculate the flow past a given profile by Theordorsen's method. Syn1 solved the inverse problem of finding the profile corresponding to a specified target pressure distribution by an extension of Lighthill's method. These programs were written for the IBM 1130. This was an early precursor of the class of machines which came to be called minicomputers. It was about the size of a refrigerator, and had only a few thousand words of memory. Coding was restricted to a subset of Fortran. Input was by punched cards, and output by a line printer. There was no graphics capability. The calculations took 5-10 minutes. These codes have survived, and now run on a laptop computer in about 1/50 second. Figure 5 illustrates a direct calculation by flo1 of the flow past a NACA 0012 airfoil. Figure 6 illustrates an inverse calculation by syn1 in which the Whitcomb airfoil is recovered from its subsonic pressure distribution. The conformal mapping techniques yield essentially exact results with quite a small number of mesh points, of the order of 72.

Flo1 and syn1 were never used at Grumman. Many years later I found them very useful for the development of hydrofoils designed to delay the onset of cavitation. They were, however, a first step towards the development of methods to calculate transonic flow, which was the major challenge at that time. Transonic flow had proved essentially intractable to analytic methods. It was also known from Morowentz's theorem that although it was possible to generate shock free solutions by hodograph methods, these were isolated

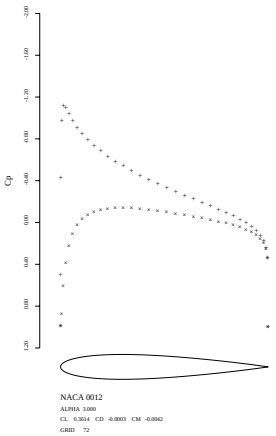


Figure 5: Direct calculation of flow past a NACA0012 airfoil

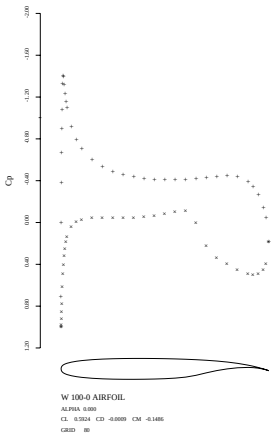


Figure 6: Inverse calculation, recovering Whitcomb airfoil

point solutions which could not be continued over a range of Mach number or angle of attack. Murman and Cole had already in 1970 introduced their mixed type scheme for the transonic small disturbance equation [1], and efforts were underway to extend their ideas to more general transonic flows. I started interacting with and subsequently joined Garabedian's group at the Courant Institute. It proved possible to treat arbitrary transonic potential flows through the rotated difference scheme [2]. For two dimensional flows this was applied after transforming the flow domain to the interior of a circle by conformal mapping, using a method originally implemented as flo2, which allowed the treatment of open trailing edges. This made it possible to add a boundary layer displacement model with a wake to correct the calculations for viscous effects.

The rotated difference scheme proved to be a very robust method, and it provided the basis for flo22, developed with David Caughey during 1974-75 to predict transonic flow past swept wings. At the time we were using the CDC 6600, which had been designed by Seymour Cray, and was the world's fastest computer at its introduction, but only had 131000 words of memory. This forced the calculation to be performed one plane at a time, with multiple transfers from the disk. Flo22 was immediately put into use at McDonnell Douglas. A full swept wing calculation took about 3 hours, at a cost of about $500. Nevertheless they found it worthwhile to perform about five calculations a day. A simplified in-core version of flo22 is still in

use at Boeing Long Beach today, and runs on a PC in about 15 seconds. At the Courant Institute we continued to look for more efficient and accurate methods, and to try to gain better understanding of issues such as numerical shock structure and the prediction of wave drag. Many of the resulting improvements were embodied in flo36, which solves the fully conservative potential flow equations by a multigrid alternating direction method. Figure 7 shows a result for the NACA 64A410 calculated in just three multigrid cycles.

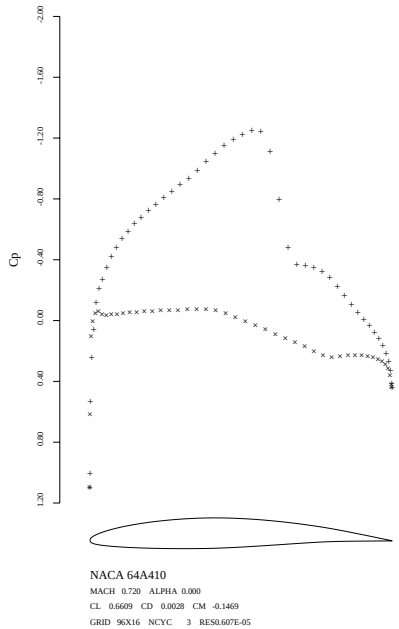


Figure 7: Pressure distribution over NACA 64A410 after three multigrid cycles

In the same period Pierre Perrier was focusing the research efforts at Dassault on the development of finite element methods using triangular and tetrahedral meshes, because he believed that if CFD software was to be really useful for aircraft design, it must be able to treat complete configurations. Although finite element methods were more computationally expensive, and mesh generation continued to present difficulties, finite element methods offered a route towards the achievement of this goal. The Dassault/INRIA group was ultimately successful, and they performed transonic potential flow calculations for complete aircraft such as the Falcon 50 in the early eighties

[3]. This was a major achievement which had a significant impact on the thinking of the CFD community world wide. It placed Dassault clearly at the fore-front in the industrial application of CFD.

By the eighties advances in computer hardware had made it feasible to solve the full Euler equations using CFD software which could be cost-effective in industrial use. In 1980 Euler solutions generally required of the order of 10,000 steps to reach a steady state, and often exhibited oscillations in the neighborhood of shock waves. These difficulties were resolved during the following decade, in the course of which a fairly complete understanding of shock capturing algorithms was achieved, stemming in particular from contributions of Godunov, Van Leer, Harten and Roe. Fast multigrid solution methods were also developed, typically using generalized Runge Kutta or LU implicit methods with some type of pre-conditioning. It has recently proved possible to refine the LUSGS multigrid method to the point where steady state Euler solutions can be obtained in 3-5 cycles [4]. This allows two dimensional calculations on a 160 x 32 grid to be performed in 1/2 second on a PC with a 2GHz Pentium 4 processor, and three dimensional calculations on a 192 x 32 x 32 grid in 23 seconds. Figure 8 shows a result for the RAE 2822 airfoil.

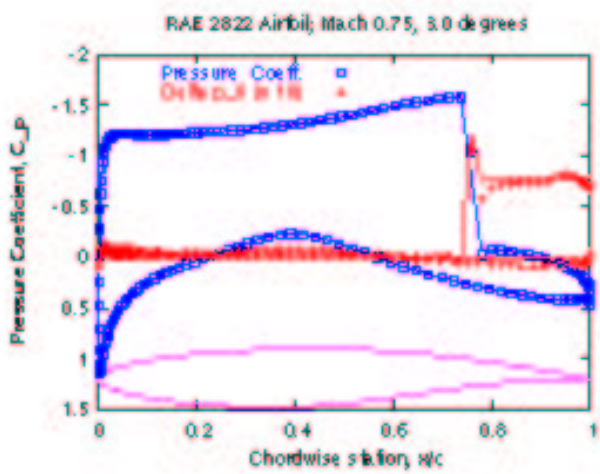


Figure 8: Transonic flow past RAE 2822 airfoil at Mach 0.75, 3.0 degrees incidence. Solution with H-CUSP scheme after three multigrid cycles

By this time I was at Princeton where, motivated by the successes at Dassault, we also mounted a major effort to develop a method to solve the Euler equations of unstructured meshes, and were finally able to calculate the flow past a complete Boeing 747, including flow through the nacelles, at the end of 1985 with the "airplane" code [5]. This software was heavily used in the NASA supersonic transport program and continues to be used at the present time. Current versions use a multigrid algorithm with fully parallel operation on multiple CPUs. This enables an airplane calculation on a mesh with 2 million cells to be performed in about 30 seconds. Figure 9 shows a simulation of the Airbus 320. Contemporary developments at Das-

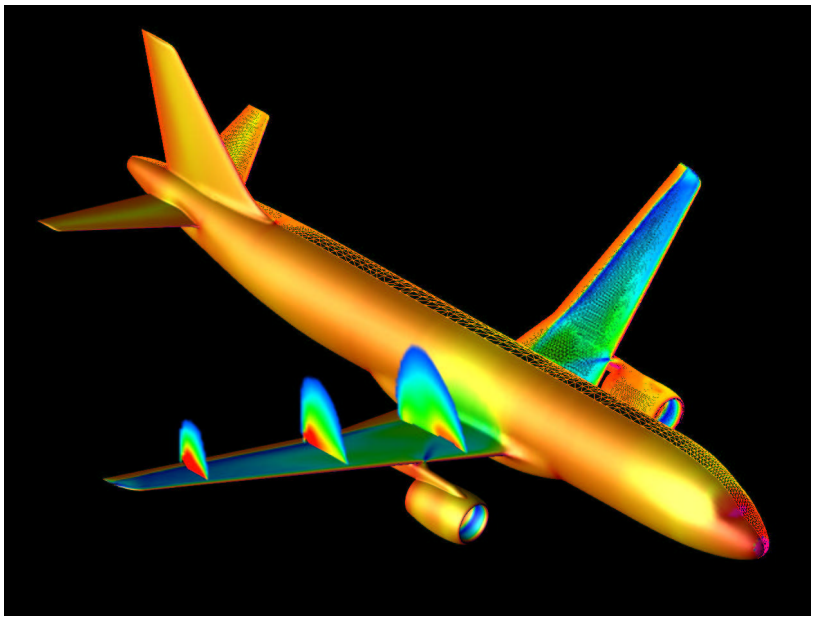

Figure 9: Airbus 320

sault led to an in-house capability to perform both Euler and Navier Stokes calculations for arbitrary configurations such as the Rafale. There was also a major effort on both sides of the Atlantic to improve the ability to predict hypersonic flow, stemming from the Hermes and NASP projects. With Dassault holding the responsibility for the aerodynamic design of Hermes, Pierre Perrier played a leading role in the sponsorship and direction of CFD research for hypersonic flow throughout Europe, and had a major influence in raising CFD capabilities to a new standard. Figure 10 shows a Hermes

calculation which exemplifies the CFD capabilities that by now existed at Dassault, which remained unmatched throughout the rest of the aviation industry.

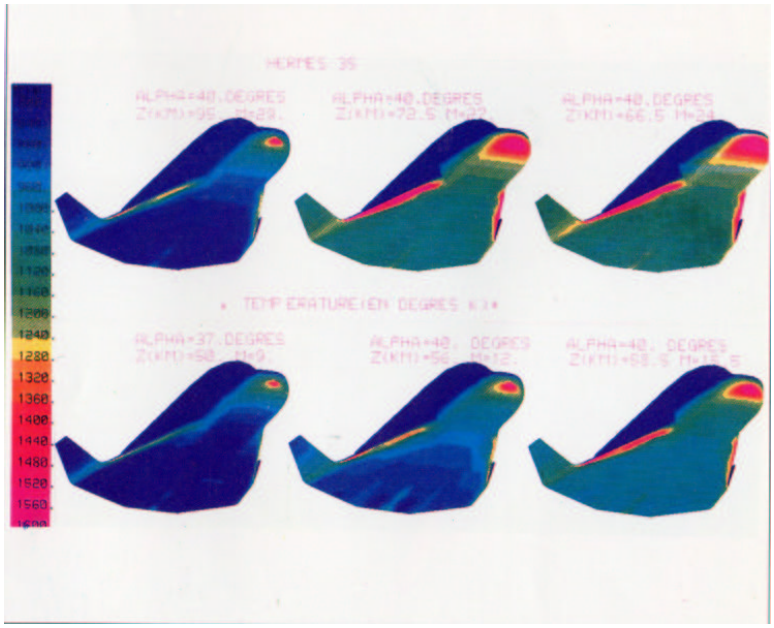


Figure 10: CFD calculation of Hermes Spacecraft, Mach 9 to 29

Today CFD can be routinely used for the analysis of complex flows, and CFD simulation of attached flows are certainly accurate enough for performance predictions. There remain difficulties in the prediction of separated and turbulent flows, which motivates continuing research on turbulence modeling, and both large eddy simulation (LES) methods and direct Navier Stokes (DNS) methods for the study of turbulence. However, the computational complexity of LES and DNS methods for high Reynolds number flows is beyond the reach of any computers foreseeable within the span of our careers unless some completely new technology were to emerge.

The effective use of CFD for design ultimately requires another level of software which can guide the designer in the search for improved aerodynamic shapes on the basis of the predicted aerodynamic performance. Pironneau already investigated the problem of optimum shape design for elliptic equations by 1984 [6]. The present author applied control theory to optimum shape design for transonic flow in 1988, deriving adjoint equations for tran-

sonic potential flow and the Euler equations which allowed the extraction of the Frechet derivative (infinitely dimensional gradient) at the cost of one flow and one adjoint solution [7]. This method has been refined over the last decade, and also extended to the Navier Stokes equations, and now provides an effective tool for wing design [8]. The last figures (Figure 11,12) show the results of Navier Stokes redesigns of the Boeing 747 wing at its present cruising Mach number of .86, and also at a higher Mach number of .90.

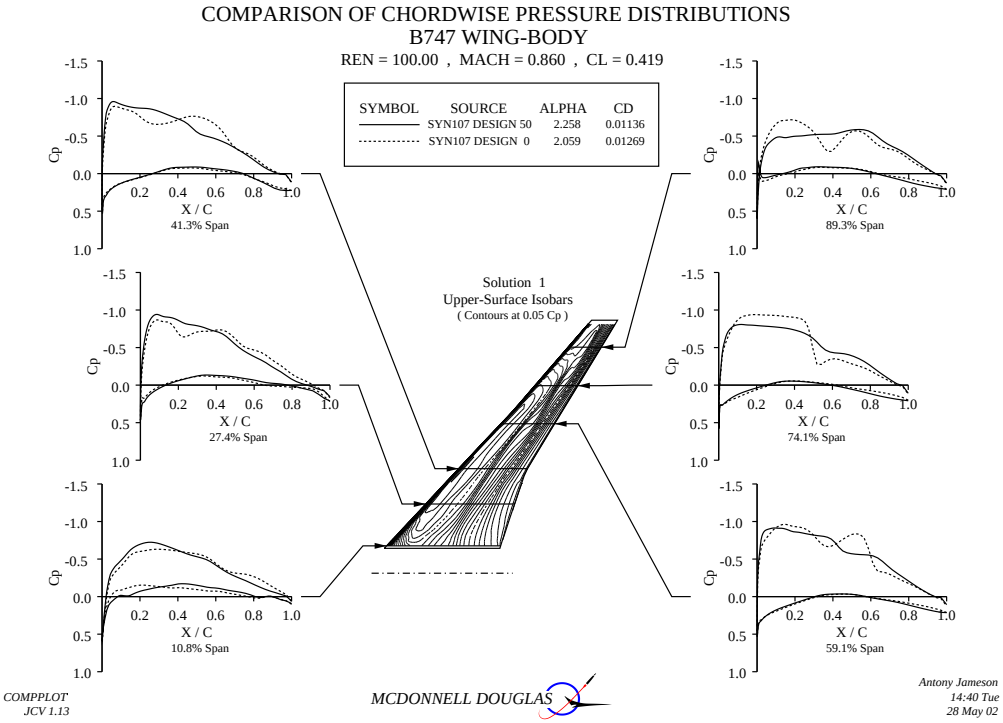


Figure 11: Comparison of Chordwise pressure distributions before and after redesign, Re=100 million, Mach=0.86, CL=0.42

The calculations are for the wing-fuselage combination, with shape changes restricted to the wing. In each case the planform was held fixed, while section changes was subject to the constraint of maintaining the same thickness. The lift coefficient and also the span load distribution were constrained to be fixed during the optimization, so that the root bending moment would not be increased, and the susceptibility to buffet would not be impaired due

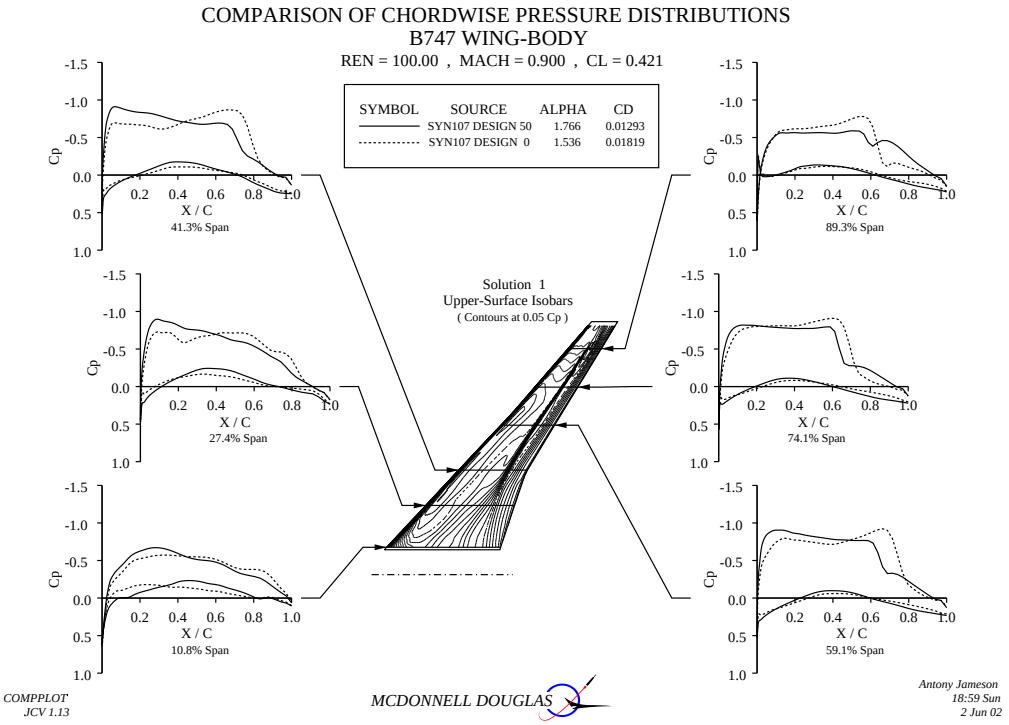


Figure 12: Comparison of Chordwise pressure distributions before and after redesign, Re=100 million, Mach=0.90, CL=0.42

to an increase in the lift coefficient of the outboard sections. At Mach .86 the drag coefficient is reduced from 126.9 counts (.01269) to 11.36 counts, a reduction of about 5 percent of the total drag of the aircraft. At Mach .90 it is reduced from 181.9 counts to 129.3 counts. Thus the redesigned wing has about the same drag at Mach .90 as the original wing at Mach .86, suggesting the potential for a significant increase in the cruise Mach number, provided that other problems such as engine integration could also be solved. Since the wing thickness and span load distribution are maintained there should be no penalty in structure weight or fuel volume. The required changes are quite subtle and there would be no hope of finding them by wind tunnel testing. Clearly there is the potential to revolutionize the design process by effective use of shape optimization technology of this kind.

The overall progress that has been achieved during the last 30 years was

unimaginable in 1970. A major factor has been the astonishing rate of improvement of computers, so that modern laptops have a performance equivalent to the super-computers of fifteen years go. But intellectual contributions such as advances in algorithms have had a roughly equal impact.

In all this the influence of Pierre Perrier's thinking has been significant and widespread. His direct involvement both with the conceptual and detailed design of a succession of Dassault aircraft together with his participation in the research efforts at Dassault gave him a unique perspective. He had the foresight to pursue a long term strategy which ultimately placed Dassault at the frontier of the industrial application of CFD.

## Acknowledgment

The results presented here were the outcome of collaborations with many colleagues and friends both in universities and in industry. The author's research during the last ten years on optimum aerodynamic shape design has also benefited greatly from the continuing support of the Air Force Office of Scientific research under a series of grants. This paper has been prepared with the assistance of Kasidit Leoviriyakit.

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