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50 years of transonic aircraft design

Antony Jameson, Kui Ou *

Aeronautics and Astronautics Department, Stanford University, United States

ABSTRACT

This article traces the evolution of long range jet transport aircraft over the 50 years since Kuechemann founded the journal Progress in Aerospace Sciences. The article is particularly focused on transonic aerodynamics. During Kuechemann's life time a good qualitative understanding had been achieved of transonic flow and swept wing design, but transonic flow remained intractable to quantitative prediction. During the last 50 years this situation has been completely transformed by the introduction of sophisticated numerical algorithms and an astonishing increase in the available computational power, with the consequence that aerodynamic design is now carried out largely by computer simulation. Moreover developments in aerodynamic shape optimization based on control theory enable a competitive swept wing to be designed in just two simulations, as illustrated in the article. While the external appearance of long range jet aircraft has not changed much, advances in information technology have actually transformed the entire design and manufacturing process through parallel advances in computer aided design (CAD), computational structural mechanics (CSM) and multi-disciplinary optimization (MDO). They have also transformed aircraft operations through the adoption of digital fly-by-wire and advanced navigational techniques.

Contents

1. Introduction

It is an honor to contribute to the 50th Anniversary Volume of Progress in Aerospace Sciences commemorating the life and work of Dietrich Kuechemann, the founder and first editor of the series. Kuechemann was one of the great aerodynamicists of his time, working first at the AVA Gottingen and subsequently, after the conclusion of the Second World War, at the RAE Farnborough. His research contributed greatly to the understanding of transonic and supersonic aerodynamics, in particular to the design of swept and slender wings. At the end of his life aerodynamics was just on the cusp of a revolution in which computational fluid dynamics (CFD) moved to the forefront of the aerodynamic design process. It is clear from Kuechemann's book [1], posthumously published in 1978, that Kuechemann was aware of the emergence of CFD as a potentially useful tool. In his section on "swept wings in

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* Corresponding author.
E-mail address: ouk@stanford.edu (K. Ou).

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transonic flow", p. 184–212, he makes several references to numerical methods. On p. 194 he stated: "In recent years, a number of numerical computer methods have been developed (see e.g. Lomax [2]). These are primarily of numerical interest and are not discussed here in detail". This perhaps reflects a view that was prevalent among aeronautical scientists of his generation that numerical methods lack mathematical content, and a resort to them represents a failure to find solutions through deep and elegant physical and mathematical insights. In fact it has become clear during the last 50 years that there is tremendous scope for mathematical depth in the formulation of modern numerical methods, as is evidenced by the mathematical foundations of the finite element method in Sobolev space, the key role of orthogonal polynomials in spectral and other high order methods, or the concept of multigrid convergence acceleration.

By the end of Kuechemann's career, as is clearly evidenced by his book, a very thorough qualitative understanding had been achieved both of the behaviors of transonic flow and of design aspects of swept wings. Kuechemann himself was a major contributor to this body of knowledge. Section 4.8 of the book contains numerous diagrams illustrating flow patterns, operational boundaries of CL and Mach number, and the onset of drag rise and buffeting. What was lacking was the capability to make precise quantitative predictions. He remarks on p. 196: "In spite of this present emphasis on numerical methods, wing design remains more of an art than an exact science, as it always has been (see also Chapter 5 of his book). In the computer methods the physics of the flow are well hidden, and design hints do not normally emerge". It has actually transpired that the capability of modern CFD methods to make very accurate predictions, together with the emergence of effective aerodynamic shape optimization methods, has converted wing design (at least of transport aircraft) to a science. Moreover information technology has completely transformed the entire design and manufacturing processes through computer aided design (CAD), which has replaced the traditional drawing board and blue prints, and computer aided manufacturing (CAM), with techniques such as numerically controlled machining (NCM). The astonishing rapidity of advances in computer hardware and software could hardly have been foreseen during Kuechemann's lifetime.

The next section gives a very brief review of the emergence and refinement of CFD since 1970. Section 3 discusses aspects of supercritical airfoil design, including the design of shock free airfoils. Section 4 discusses the application of CFD to swept wing design. Section 5 gives an overview of the way in which all aspects of aircraft design, manufacturing and operation have been completely transformed by rapid advances in computers and information technology.

2. Emergence of CFD

2.1. Early history

The history of numerical techniques for fluid mechanics has followed the trend of developing methods for solving increasingly accurate representations of the physics, for a given level of geometrical complexity, in the hierarchy of mathematical models. These models range from the small-disturbance potential equation to direct numerical simulation (DNS) of turbulent flows. The early history of important ideas and achievements, dating from before Symposium Transsonicum II includes the development of Riemann-based schemes for gas dynamics by Godunov [3]. This work was published by Godunov in the Soviet Union as early as 1959, but was not appreciated in the West for more than a decade. In fact it appears that Kuechemann was completely unaware of Godunov's work. The multigrid method suffered a similar fate. After being developed for the Laplace equation in 1964 by Fedorenko [4], it lay undiscovered in the West until the early 1970s. Research at the Courant Institute on hyperbolic systems of conservation laws led to the development, in 1960, of the first second-order accurate dissipative methods for these problems by Lax and Wendroff [5]. This class of methods forms the basis of the efficient explicit method developed in 1969 for the Navier–Stokes equations by MacCormack [6]. At the Douglas Aircraft Company, the aerodynamic research group, led by A.M.O. Smith, developed the first panel method for three-dimensional, linear, potential flows [7], and the first implementation of Keller's box method for turbulent boundary layer flows [8].

2.2. The (nonlinear) potential revolution

A major breakthrough was accomplished by Murman and Cole [9] with their development of type-dependent differencing in 1970. They obtained stable solutions by simply switching from central differencing in the subsonic zone to upwind differencing in the supersonic zone, and using a line-implicit relaxation scheme. Their discovery provided major impetus for the further development of CFD by demonstrating that solutions for steady transonic flows could be computed economically. Fig. 1, taken from their landmark paper, illustrates the scaled pressure distribution on the surface of a symmetric airfoil. The Murman–Cole scheme was extended to the full, nonlinear potential equation with the rotated difference scheme of Jameson [10]. One of the most successful, and widely used, implementations of that scheme was the FLO22 code for calculating the transonic potential flow past three-dimensional, swept wings [11]. In spite of the non-conservative formulation of Jameson's scheme used in FLO22, many aircraft companies have calibrated its behavior and the code still is used today in several companies for preliminary design. It is useful in this role, as it is capable of computing three-dimensional flow fields on grids containing about 150,000 cells in less than 15 s on a laptop computer (having a 1 GHz processor speed). Murman and Cole's original scheme also was not fully conservative, with the result that it did not enforce correct jump conditions across shocks. In fact, in one-dimensional flow the scheme allows a range of solutions. Murman soon devised a fully conservative version of the scheme [12]. In a one-dimensional model, this could still allow

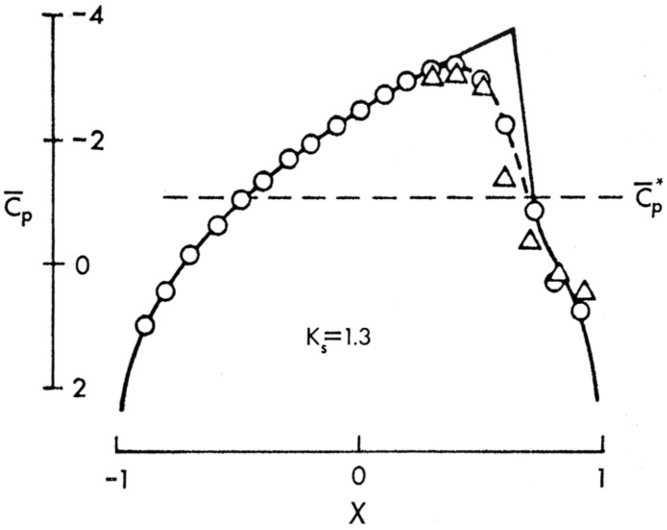

Fig. 1. Scaled pressure coefficient on surface of a thin, circular-arc airfoil in transonic flow, compared with experimental data; from Murman and Cole [9].

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(multiple equilibrium points with combinations of compression and) entropy-violating expansion shocks. However, with a judicious choice of the iterative method, these prove to be unstable equilibrium points that would not be obtained in practice. Stable, fully conservative schemes for the full potential equation were subsequently devised through the interpretation of upwinding as a controlled form of numerical diffusion; see, e.g., Jameson [13] and Holst [14]. Jameson's fully conservative scheme for the full potential equation was also presented in Gottingen at the second Symposium Transsonicum [15]. Although the type-dependent schemes resulted in a major reduction in computer time required for steady solutions of transonic flow problems, considerable further efficiency was possible through use of the multigrid algorithm. After Fedorenko's development of the method in the 1960s, it was discovered, further developed, and popularized by Brandt in the 1970s [16]. Multigrid was applied to the transonic small-disturbance equation by South and Brandt [17], and to the full potential equation by Jameson [18]. Just as solution of the full potential equation for transonic flows with shock waves was becoming relatively efficient, it was discovered by Steinhoff and Jameson [19] that solutions to the steady potential problem for certain flows containing zones of supersonic flow terminated by shock waves exhibited non-uniqueness. They actually obtained a triple solution for a symmetric Joukowsky airfoil at zero angle of attack, corresponding to a reversal of the lift slope C_{L_α} in a critical Mach number range around $M_\infty = 0.80$, and a pitchfork bifurcation. This provided further impetus for the development of techniques to solve the Euler and Navier–Stokes equations for these flows. By this time, full potential solutions for three-dimensional wing geometries had become fairly routine, and the solution for a complete Falcon 50 business jet configuration, including horizontal and vertical tails and engine nacelles, was presented by Bristeau et al. [20] using a finite-element formulation.

2.3. *Solution of Euler equations*

The solution of the Euler equations became a central focus of CFD research in the 1980s. Most of the early solvers tended to exhibit pre- or post-shock oscillations. Also, in a workshop held in Stockholm in 1979 [21] it was apparent that none of the existing schemes converged to a steady state. The Jameson–Schmidt–Turkel (JST) scheme [22], which used Runge–Kutta time stepping and a blend of second- and fourth- differences (both to control oscillations and to provide background dissipation), consistently demonstrated convergence to a steady state, with the consequence that it became one of the most widely used methods. The issues of oscillation control and positivity had already been addressed by Godunov in his pioneering work in the 1950s (translated into English in 1959). He had introduced the concept of representing the flow as piecewise constant in each computational cell, and solving a Riemann problem at each interface, thus obtaining a first-order accurate solution that avoids non-physical features such as expansion shocks. When this work was eventually recognized in the West, it became very influential. It was also widely recognized that numerical schemes might benefit from distinguishing the various wave speeds, and this motivated the development of characteristics-based schemes. The earliest higher-order characteristics-based methods used flux-vector splitting [23], but suffered from oscillations near discontinuities similar to those of central-difference schemes in the absence of numerical dissipation. The Monotone Upwind Scheme for Conservation Laws (MUSCL) of Van Leer [24] extended the monotonicity-preserving behavior of Godunov's scheme to higher order through the use of limiters. A general framework for oscillation control in the solution of non-linear problems is provided by Harten's demonstration that total variation diminishing (TVD) schemes are monotonicity-preserving [25]. Roe's introduction of the concept of locally linearizing the equations through a mean value Jacobian [26] had a major impact. It provided valuable insight into the nature of the wave motions and also enabled the efficient implementation of Godunov-type schemes using approximate Riemann solutions. Roe's flux-difference splitting scheme has the additional benefit that it yields a single-point numerical shock structure for stationary normal shocks. Roe's and other approximate Riemann solutions, such as that due to Osher, have been incorporated in a variety of schemes of Godunov type, including the essentially non-oscillatory (ENO) schemes of Harten et al. [27]. The use of limiters dates back to the flux-corrected transport (FCT) scheme of Boris and Book [28]. They demonstrated essentially perfect propagation of discontinuities at the first AIAA CFD Conference in Palm Springs [29]. The switch in the JST scheme [22] can actually be reformulated so that the scheme is local extremum diminishing (LED), and may be interpreted as an example of a symmetric limited positive scheme [30,31]. Euler solutions for a complete aircraft configuration, computed on an unstructured, tetrahedral mesh, were presented by Jameson et al. [32]. This method was essentially equivalent to a Galerkin method with linear elements, stabilized by artificial diffusion to produce an upwind bias. Other finite-element methods also have been developed to solve the Euler equations; an example is the

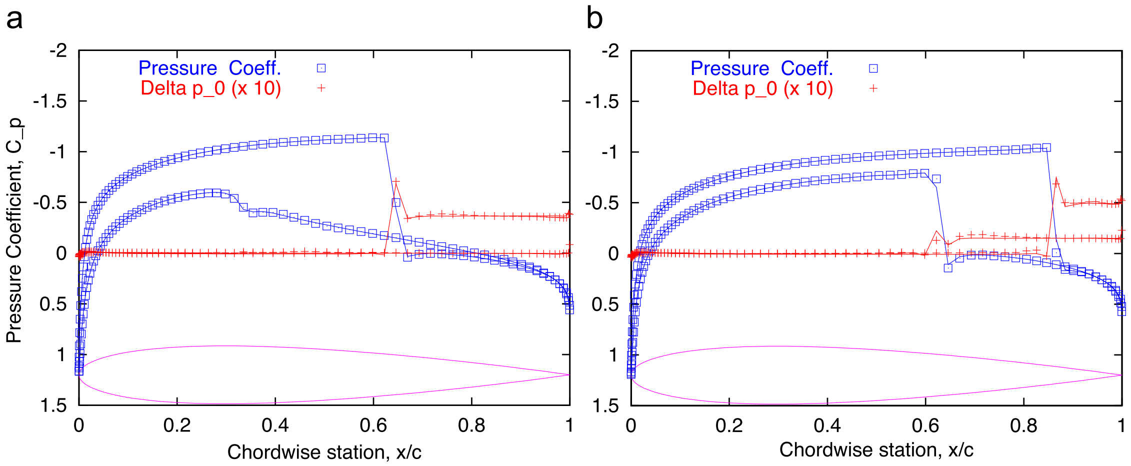

Fig. 2. Surface pressure and entropy distributions for flow past the NACA0012 airfoil at (a) $M=0.80$ and $\alpha=1.25$ degree incidence and (b) $M=0.85$ and $\alpha=1.0$ degree incidence. Solutions on 160×32 cell grids after 5 multigrid cycles (symbols) are compared with solutions iteratively converged to machine zero (lines).

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Streamwise Upwind Petrov–Galerkin (SUPG) method (Hughes et al. [33], Kelly et al. [34], Peraire et al. [35]; see also Zienkiewicz and Taylor [36]) which automatically incorporates an upwind bias by an appropriate choice of test functions. Implicit schemes based on the Alternating-Direction Implicit approximate factorization for Euler and/or Navier–Stokes equations were introduced independently by Briley and McDonald [37] and by Beam and Warming [38]. A multiple grid algorithm for the Euler equations was developed by Ni [39], and for the Runge–Kutta algorithm by Jameson [40]. Jameson's scheme was a cell-centered finite-volume scheme that created coarse grids by agglomerating the fine grid cells in groups of four (in two dimensions) or eight (in three dimensions). Subsequently, the idea of agglomeration multigrid has been extended to unstructured grids (Smith [41], Lallemandetal. [42], Venkatakrishnan and Mavriplis [43]; see also Mavriplis [44]). Implicit schemes based on the lower–upper (LU) factorization were introduced by Jameson and Turkel [45], and an efficient multigrid implementation of the LU scheme has recently been demonstrated by Jameson and Caughey [46]. The latter scheme seems to hold the record for convergence of solutions to the Euler equations for two-dimensional flows past airfoils, producing results converged to within truncation error in 3–5 multigrid cycles for a number of test cases. Fig. 2 shows the surface pressure and entropy distributions for the flow past the NACA0012 airfoil at two transonic conditions. These same conditions were used as standard test cases for the 1979 GAMM Workshop in Stockholm, where up to 5000 iterations were required for convergence of most algorithms presented [21].

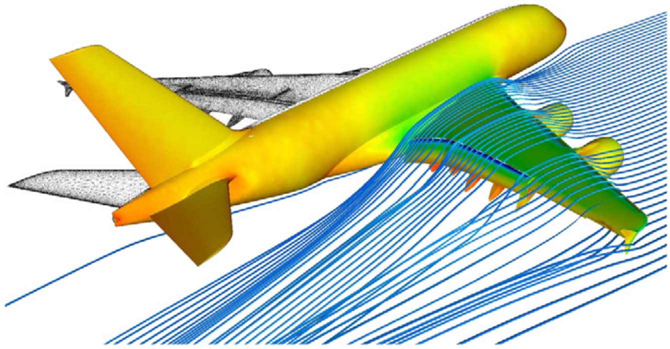

Fig. 3. CFD simulation performed by DLR of flow over a complete A380.

2.4. *Solution of the Navier–Stokes equations*

After 1985 the successful shock capturing algorithms for the Euler equations were rapidly extended to solution of the Reynolds averaged Navier–Stokes (RANS) equations. The last two decades have seen the emergence of very complex software systems for flow simulation, integrating geometric modeling, mesh generation, numerical solution and post-processing. Some of these have been developed by national research institutes. Notable examples include the DLR's Megaflow system which includes options for solution on both structured grids (FLowER) and unstructured grids (TAU). NASA counterparts include Overflow, FUN3D and USM3D. Fig. 3 and 4, supplied by Norbert Kroll, illustrate the kind of way in which CFD is now used in transport aircraft design.

Commercial CFD software capable of simulating very complex flows has also become widely available. Notable examples include Fluent, CFX, Fastran and CFD++. Some of the most stunning applications have been in the simulation of Formula racing cars using grids with 100 million or more cells.

2.5. *Optimum shape design*

The formulation of (inverse) design methods for aerodynamic problems dates to the method based on conformal mapping of Lighthill [47]. For transonic flow problems, the earliest design methods were based on the hodograph method (see, e.g., the numerical hodograph methods of Nieuwland [48] and Boerstoel and Uijlenho [49]). The complex characteristics method of Garabedian

Fig. 4. Example of growing use of CFD in today's Airbus A380.

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and Korn [50] and the fictitious gas airfoil design method, inspired by earlier experimental work with a rheo-electrical analog approach [51], led to further advances. Direct transonic potential flow solvers were coupled with optimization procedures by Hicks and Henne to design transonic airfoils and wings [52]. Pironneau used optimal control techniques for the design of shapes governed by elliptic equations [53]. Subsequently Jameson developed the use control theory [54], based on the solution of adjoint problems, and applied it with Reuther to the design of aerodynamic shapes in transonic and supersonic flow governed by (nonlinear) potential flow [55] and the Euler equations [56], and (with Martinelli and Pierce) to problems governed by the Navier–Stokes equations [57,58].

3. Transonic airfoil design

Kuechemann discusses transonic flow patterns for airfoils in considerable detail on pp. 185–192 of his book, referring particularly to the work of Pearcy [59] who proposed the concept of “peaky” airfoil with a strong leading edge suction peak in subsonic flow. This tends to produce a flat topped pressure distribution when the flow becomes transonic. This concept was further extended by Whitcomb in his supercritical airfoil design [60]. Whitcomb combined a peaky leading edge design with a strongly cambered lower surface near the trailing edge which produced a significant increase in the lift coefficient from the rear loading. Kuechemann does not refer to Whitcomb’s airfoil, but he does refer to Whitcomb’s transonic area rule.

Kuechemann also refers on p. 189 to the “transonic controversy” over whether airfoil producing shock-free transonic flows could be produced. It had been proved by Cathleen Morawetz [61] that a shock free transonic flow must be on isolated point, such that any perturbation of the shape or the free stream conditions would produce a shock wave. Nieuwland actually succeeded in producing some shock free airfoils by a design method in the hodograph plane [48]. Shortly thereafter Garabedian developed his method of complex characteristics in the hodograph plane as a powerful tool for designing shock free airfoil. Kuechemann includes a figure showing the best known of these airfoils, the Garabedian–Korn airfoil, on p. 190. This airfoil was very influential in the subsequent development of transonic wing design. It has also been a source of consternation because many CFD codes have not been able to reproduce a shock free solution for which it was designed.

The coordinates calculated by the hodograph method are not perfectly accurate because of integration errors. Recent calculations suggest that the Garabedian–Korn airfoil is actually shock free at Mach 0.7510 and CL 0.6250, not the originally calculated design point of Mach 0.7500 at CL 0.6290. This is illustrated in Fig. 5a which shows an Euler solution calculated on an extremely fine mesh with 5120 intervals around the profile and 1024 intervals normal to the airfoil for a total of 5,242,880 mesh points. Fig. 5b shows that there is a double shock at the original design point Mach 0.7500 and CL 0.6290, consistent with Morawtz’s theorem. In these figures the negative pressure coefficient is plotted vertically, while the right hand window shows the Mach contours.

The boundary layer displacement effect would prevent the flow from being shock free in practice. In order to overcome this difficulty Garabedian adopted the practice of designing airfoils with an open trailing edge, so that the estimated boundary layer displacement thickness could be subtracted. Since, however, the boundary layer thickness varies with the Reynolds number, this leads to a situation where a shape that produced shock free flow in flight would not do so in a wind tunnel, and vice versa.

Nevertheless the outcome after 50 years is that most modern transonic commercial aircraft including business jets as well as airliners have wing sections that strongly resemble the Garabedian–Korn airfoil.

4. Swept wing design

Due to three-dimensional effects a satisfactory swept wing cannot be designed with a fixed wing section from root to tip. In order to obtain a satisfactory span load distribution it is actually necessary to twist the tip down relative to the root. For a wing with 35° of sweep the total twist needed is about 8°. While an elliptic span load distribution would minimize the induced drag, it is actually better to have a more inboard loaded distribution which reduces the root bending moment and correspondingly the structure weight. Wings of commercial transport aircraft usually have an extended chord in the inboard region to facilitate the accommodation of the landing gear. The resulting highly tapered planform may lead to high section lift coefficients in the outboard wing. This in turn may lead to strong shock waves when the total lift coefficient is increased, resulting in shock induced separation and buffeting. It is also generally desirable to increase the depth of the inboard wing sections as much as possible in order to reduce the structure weight and provide more fuel volume.

In Kuechemann’s own research he made important contributions to the understanding of three-dimensional effects on swept wings. He discusses the design of swept wings at length in Chapter 5 of his book. On p. 223 he suggests the desirability of maintaining a fully swept isobar pattern over the wing. On the following page he goes on to suggest that the aerodynamic design aims can be stated in the form of a required pressure distribution for a specified Mach number and lift coefficient. This approach would require the availability of a method to solve the inverse problem of finding the geometry which corresponds to a given pressure distribution. Since no such geometry necessarily exists this can lead to an ill-posed problem. This difficulty can be avoided by reformulating the problem as an optimization problem where the geometry is selected to minimize a cost function of the form:

$$I = \int (p - p_T)^2 \, ds$$

where p_T is the target pressure and the integral is over the wing surface.

The development during the last 20 years of aerodynamic shape optimization techniques based on control theory enables the effective solution of both the inverse problem and the problem of minimizing drag at a given lift. The author’s SYN107 program performs aerodynamic shape optimization for wing-fuselage combinations with the flow modeled by the RANS equations. In order to obtain good wing performance it is important to account for the effects of the fuselage. Moreover transonic flow is so sensitive that the shape modifications needed to optimize the wing may be no larger than the boundary layer displacement thickness, with the consequence that viscous effects need to be included in the optimization.

The following example illustrates the process of wing design via aerodynamic shape optimization. An initial wing was created by substituting the Garabedian–Korn section into the planform of a representative modern transonic wing design, the NASA Common Research Model (CRM), which is the test shape for the latest AIAA Drag Prediction Workshops [62]. After scaling the thickness to produce a distribution similar to the CRM, and introducing 7° of twist to produce a near elliptic spanwise lift distribution, the result calculated using the Reynolds averaged Navier–Stokes equations at a design point of Mach 0.850 and CL 0.440 is as shown in Fig. 6a. In this calculation the Reynolds

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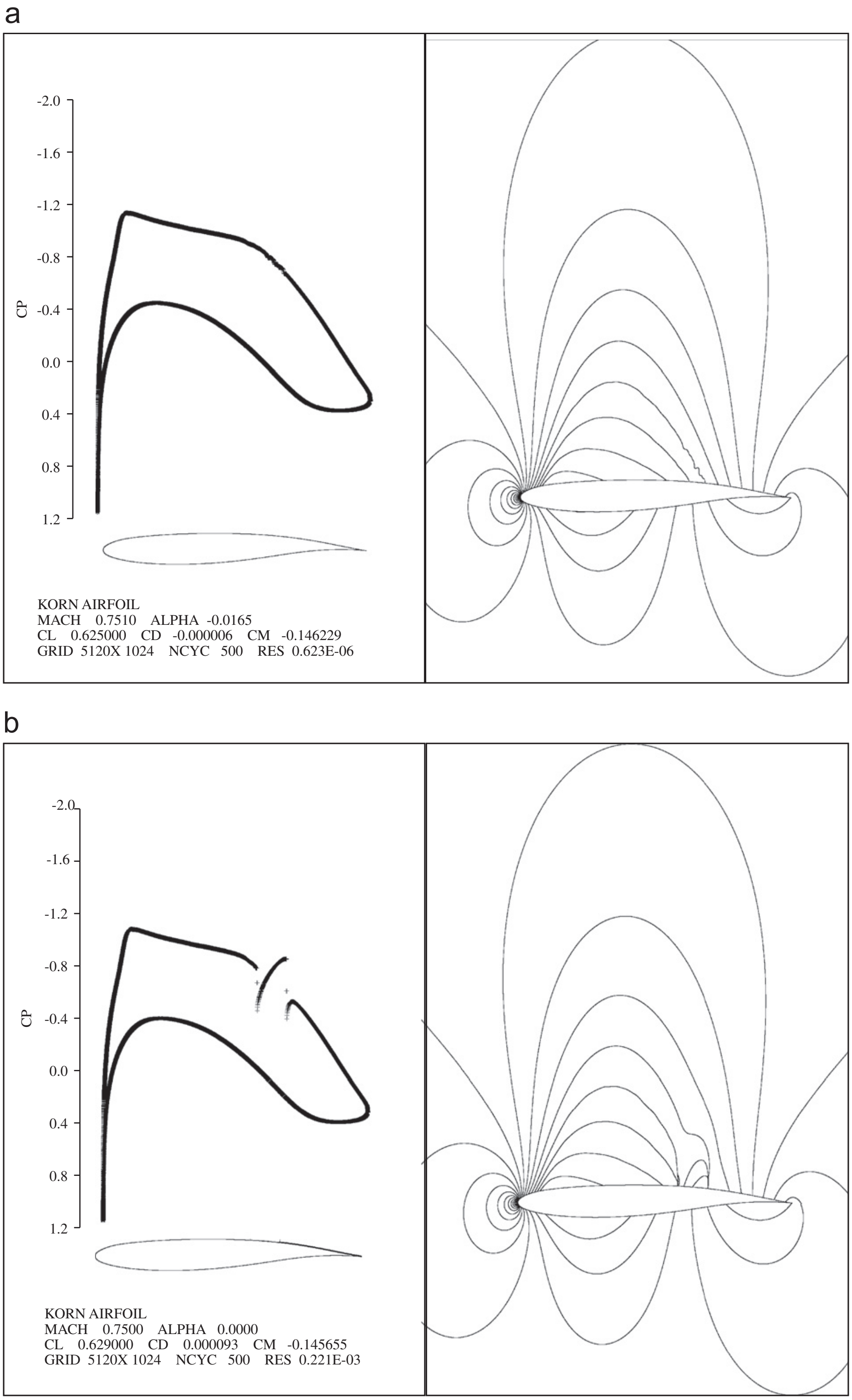

Fig. 5. Euler solution of transonic flow over a Garabedian–Korn airfoil (a) at the new design point (shock free) and (b) at the original design point (with strong double shock).

number is 20 million based on the CRM reference chord. It can be seen that there is a very strong shock wave across the entire span. However, using the optimization method based on techniques drawn from control theory, the wing can be redesigned to produce an essentially shock free flow as illustrated in Fig. 6b. The outboard wing sections are preserved almost unchanged, but a substantial modification is required near the fuselage. This wing is a single point design, and it turns out that it incurs a significant drag penalty below the design point at Mach numbers in the range 0.83–0.84 due to the formation of a strong double shock.

A more balanced design is obtained by using the single point design as the initial shape for a multipoint design in which the average drag coefficient at Mach 0.82, 0.83, 0.84, 0.85 and 0.86 is minimized at CL of 0.44. The performance of the resulting wing is shown in Fig. 7, in which it can be seen that the drag of the

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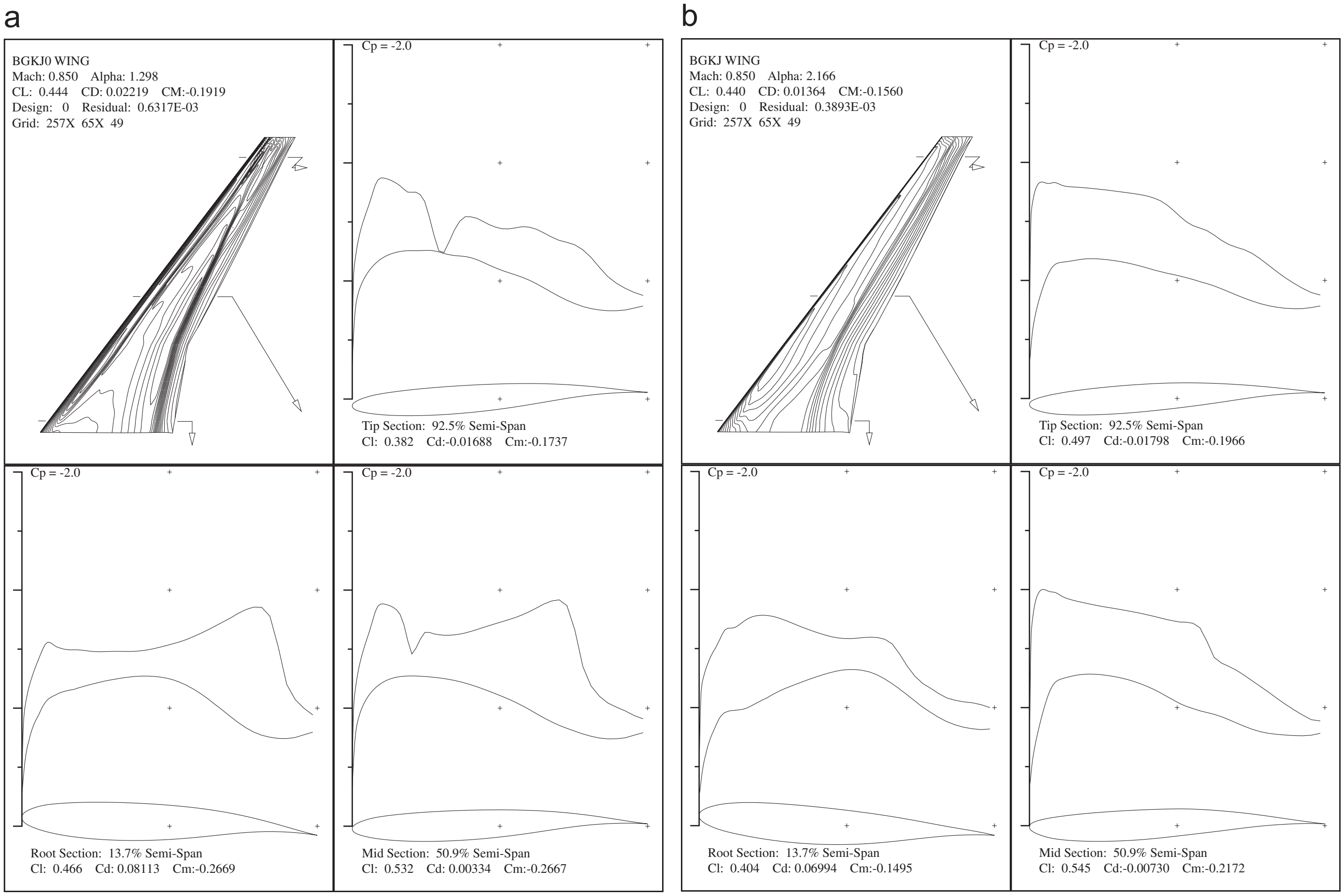

Fig. 6. Pressure contours for the CRM wing (a) before optimization (with strong shock) and (b) after optimization (with very weak shock).

exposed wing (including friction drag) is almost constant at 0.0136 (136 counts) at Mach 0.82, 0.83 and 0.84, rising to 138 counts at Mach 0.85. This is slightly less than the drag of the CRM, and demonstrates that a competitive wing can be obtained in two calculations starting from the Garabedian–Korn section. The first calculation took 4 h and the second 6 h using a quad-core workstation which is about 5000 times faster than the Control Data 6600 computers at the Courant Institute in the early 1970s, and has about 8000 times the memory. Evidently such calculations would not have been feasible in that era.

5. Other aspects of aircraft design

In the previous sections we have discussed the aerodynamic design of aircraft using CFD. It is evident, and proven in the aircraft industry, that use of computational aerodynamic analysis and design optimization have led to vast improvement in the lift, drag and performance characteristics of aircraft. Having achieved this, it is equally important to keep in mind the multidisciplinary nature of aircraft design. On the one hand, an aircraft needs to be aerodynamically efficient to stay competitive. On the other hand, it is also important for the aircraft to be safe, stable, controllable by the pilots, and manufacturable. At the end of Chapter 5 in his book, Kuechemann expressed a similar view: ‘‘Nevertheless, this work gives a clear indication of the strong and necessary trend to integrate ever more closely the aerodynamic design of aircraft with that of stability, control, and guidance systems and with the structural design’’. In this section we discuss briefly these other aspects of aircraft design and point out that the application of computers have profound implications on all aspects of aircraft design.

5.1. Stability and control

The late 1960s and early 1970s, towards the later part of Kuechemann's life, saw the incipience of a computer revolution. Supercomputers, such as Control Data 6600 in 1964, began to appear and grow rapidly. Moore's Law was stated in 1965, and by the early 1970s the first microprocessors, such as Intel 4004 and Motorola 6800, also started to appear. The development of supercomputers has been instrumental in driving the development of computational fluid dynamic methods and algorithms. Similarly, the development of microprocessors and digital computers have enabled a parallel revolution in the field of aircraft stability and control, and led to the digital fly-by-wire (FBW) system. The Concorde, which first flew in 1969, was the first civil airliner to have an electrical analog fly-by-wire flight control system installed (it is of interest to note that Kuechemann played an important role in contributing to the advanced ogive shape used on Concorde). The analog system was later replaced by the first generation of electrical flight control systems with digital technology. The General Dynamics F16 was the first military aircraft with a full digital fly-by-wire control systems. Led by Ziegler, a former fighter pilot, Airbus was the first company to use fly-by-wire for civil aircraft, the Airbus A320, and soon after FBW control systems were adopted for the Airbus 330 and 340, and the Boeing 777. The fly-by-wire control system has been credited with key role in the successful engine out descent of an Airbus 320 on the Hudson River after a bird strike.

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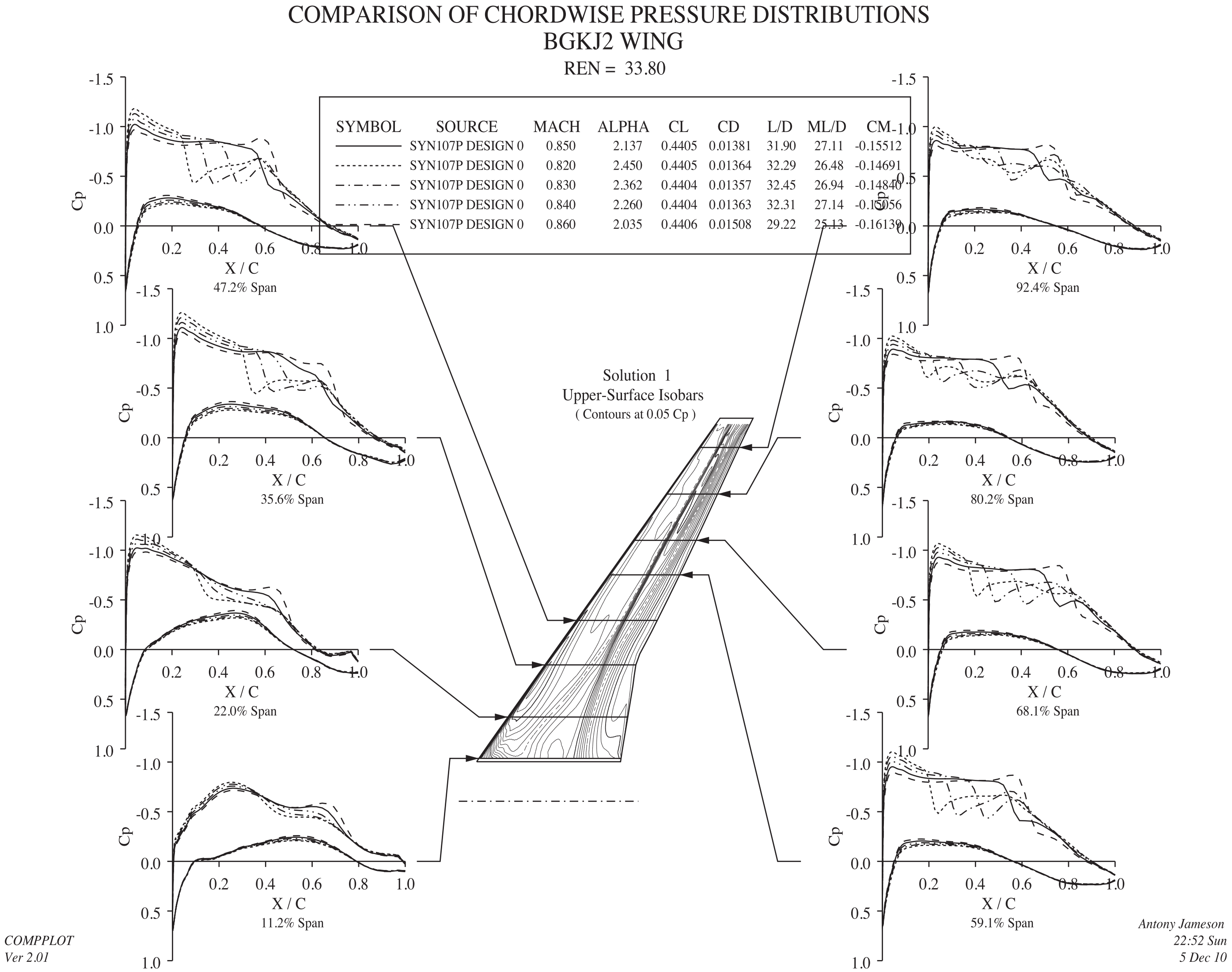

SYMBOL	SOURCE	MACH	ALPHA	CL	CD	L/D	ML/D	CM
————	SYN107P DESIGN 0	0.850	2.137	0.4405	0.01381	31.90	27.11	-0.15512
- - - - - -	SYN107P DESIGN 0	0.820	2.450	0.4405	0.01364	32.29	26.48	-0.14691
— · — · —	SYN107P DESIGN 0	0.830	2.362	0.4404	0.01357	32.45	26.94	-0.14840
— · · — · · —	SYN107P DESIGN 0	0.840	2.260	0.4404	0.01363	32.31	27.14	-0.15056
— — —	SYN107P DESIGN 0	0.860	2.035	0.4406	0.01508	29.22	25.13	-0.16139

Fig. 7. Multipoint design optimization result for the redesigned CRM wing that started with the Garabedian–Korn section. The design points are Mach = 0.82, 0.83, 0.84, 0.85, and 0.86 at fixed CL = 0.44.

In a fly-by-wire system digital controls replace the conventional mechanically signaled flight controls. The elimination of mechanical components in the new digital system are clearly illustrated in Fig. 8. The pilot no longer physically move the control surfaces through mechanical linkages. Instead the pilot's commands, or the orders from the autopilot computers (when in autopilot mode) are transmitted digitally to a group of flight computers which instantly interprets and analyzes the control inputs and evaluate the aircraft's speed, weight, atmospheric conditions, and other variables to arrive at the optimum control deflections. The flight control surfaces are then electrically controlled by the computers and hydraulically activated. The replacement of the conventional mechanical components with electrically transmitted signal along wires leads to the name fly-by-wire. Realization of the fly-by-wire system is not possible without the development of digital flight computers and microprocessors that enable a fail-safe flight control system to be implemented economically, safely, and reliably.

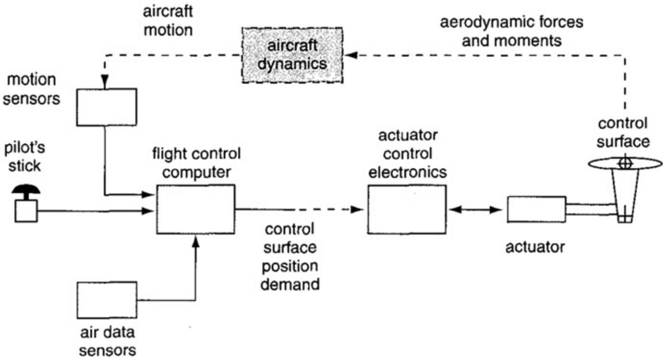

Fig. 8. Schematic illustration of a digital fly-by-wire system. Figure courtesy of [63].

According to Collinson [63], the major building blocks of a digital FBW system consist of, as illustrated in Fig. 9, a group of flight control computers, electrical data transmission system, actuator control electronics, aircraft motion sensors, and air data sensors. As discussed before the flight computers take in all the information including pilot's order, the aircraft's current state and its external environment, and move the control surfaces to follow the desired flight path while at the same time achieve good handling quality and make sure the airplane is not over-stressed beyond its flight envelope. There are multiple computers for redundancy. These computers are designed and manufactured

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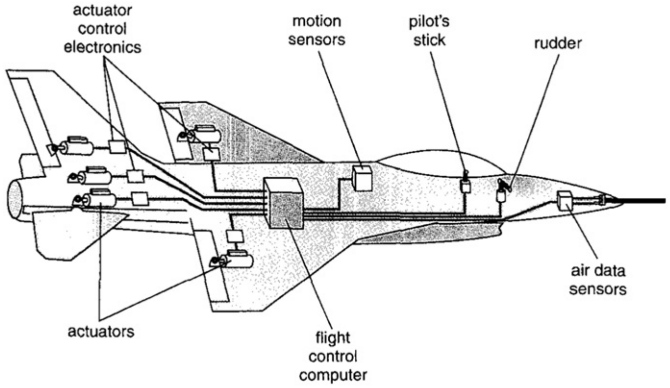

Fig. 9. Major elements of a digital fly-by-wire system. Figure courtesy of [63].

by different equipment manufacturers to make them tolerant to a design or manufacturing fault. Within each computer, there are multiple channels performing control as well as monitoring functions to check faults and failures. Furthermore, each channel has multiple dissimilar processors with their own power supplies and softwares. Software programs are also written by different groups for different manufacturer's microprocessors to avoid common errors. The electrical data transmission system is a network of wires and electronics that code, transmit, receive, and decode the digital signal. It also features multiple redundancy and has high data transmission rate. On the airplane control surface actuators end, there is the FBW actuation system. The system is designed to be failure tolerant by again having multiple independent actuators and sensors. Sophisticated voting and consolidation algorithms help to detect and isolate failures in the event of faults occurring in any of the actuators. Another advantage of digital FBW actuation is the faster control surface position feedback that significantly increases actuation response speed. Fast FBW system response is crucial for keeping aerodynamically unstable airplane from divergence. The resulting control surfaces movements translate into aircraft motions, which need to be sensed and made known to the flight computers. The motion sensors do this by measuring the acceleration and angular rotation speed along the pitch, roll, and yaw axes of the aircraft. The motion sensors also detect aircraft deviations due to external disturbances and feed them back to the flight computers, which will then make timely adjustment. Finally, sensors to measure the air data are also essential. Incidence angle measurements, such as pitch and yaw angles, are needed for pitch and rudder control and to avoid stall. Due to the variation in speed and air density, the control surface effectiveness at different point in the flight envelop is different. To achieve similar flight handling quality throughout the flight envelope, the airspeed, flight altitude, and Mach number measurements help the flight computers to compensate for the variations. The air data sensor unit uses microprocessor to perform air data computations.

Traditionally, aircraft designers have been confined to design aircraft with strong natural stability to prevent large deviations following a disturbance. However, this made the system harder to maneuver. Kuechemann called it "one of the fundamental conflicts in the dichotomy of stability and control". The invention of digital FBW systems has removed this constraint. It is now possible to reduce the natural stability and, in return, reduce the aircraft weight and drag by having smaller control surfaces. Kuechemann also regarded 'the establishment of reasonable and safe handling criteria and their attainment' as 'the central and most important task in aircraft design'. We conclude this brief section on FBW systems by noting that this has been achieved by digital FBW, firstly by providing the pilot with constant good control and handling characteristics over the whole flight envelope and under all loading conditions, and secondly by providing flight envelope protection which prevents the aircraft from stalling and from exceeding its structural limit loads. Digital flight control systems make flying safer and more economical for the transport aircraft, and more comfortable for the pilot as well as the passengers.

5.2. *Computer aided design and manufacturing*

For the aircraft designers, the availability of the computer and its associated tools not only frees them from certain design constraints, but also allows them to rethink the aircraft design process in a more integrated and efficient way. We discuss the significance of computers on the traditional aircraft design process in the current section, focusing on the impact of computer aided design (CAD) and computer aided manufacturing (CAM).

In the early years, geometric modeling technology was driven by the automotive and aircraft industries due to their unique engineering requirements for a wide range of curves and surfaces for their parts. Manually defining and manufacturing these components were becoming increasingly time-consuming and costly. By the early 1960s, numerically controlled machine tools became more readily available. There was the need to generate the digital information to drive these machines. CAD systems began to emerge in this era. As in the case of CFD and digital FBW systems, CAD system development also experienced rapid changes as computer hardware became more capable. In the 1960s, CAD software was run on mainframe computers. The earliest CAD systems were used primarily for replacing the traditional drafting practice. Though limited at that time to handle only two-dimensional data, using CAD for engineering drawing helped to reduce drawing errors and allowed the drawings to be modified and reused. Large aerospace and automotive companies with the resources to cover the high costs of early computers became the earliest users of CAD software. Most CAD development in that period was conducted internally in those companies. An example was the CADAM system developed by the Lockheed aircraft company. This later evolved into the very successful CATIA system developed by Dassault. In the 1970s, the emergence of powerful minicomputers made CAD software more affordable and accessible, and helped create the commercial CAD software market. Very rapid growth of commercial CAD changed the way CAD was used and developed in big automotive and aerospace companies as they began to use commercial software in conjunction with their internally developed CAD systems. Simultaneously there were significant advances in the geometric algorithms that CAD software was based on. Major developments include the Bezier curves and surfaces [64], B-splines [65], and Non-Uniform Rational B-Splines (NURBS) [66]. In the 1980s, low-cost, low-maintenance, and high-performance workstations using UNIX operating system were introduced. This again revolutionized the CAD software market, and effectively replaced the mainframe and mid-range computers as the preferred hardware for CAD systems. At the same time, three-dimensional CAD software and solid modeling became commercial reality. As the computer hardware and maintenance costs continued to fall and CAD software became more available and powerful, commercial CAD systems spread throughout industry. In 1988 Boeing made the decision to use the commercially available CATIA to design and draft the new B777 airplane, which became the first CAD based "paperless" design. This decision proved to be very successful, leading to reduced product development time and cost. From the 1990s to the present time, the same trend we have observed

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repeated itself, with more cost-effective and powerful personal computers replacing the less cost-effective workstations, and with a corresponding migration of CAD software from the Unix system to the mainstream Windows and Linux operating systems. The function of CAD systems also evolved from pure geometric modeling tools into a system of computer aided engineering solutions that consists of computer aided manufacturing, digital assembly, and virtual production management.

The usefulness of computers in today's aircraft industry can be appreciated by considering two examples of challenges facing an aircraft company as the organization grows bigger and the aircraft product becomes more complicated. The first challenge is related to the increasing sophistication of the modern aircraft. As the products become more complex with more people taking part in the engineering and manufacturing process, efficient coordination and information flow become very difficult. For example, the development of the Boeing 747 airplane involved millions of parts and required the participation of thousands of engineers and manufacturing personnel. It becomes nearly impossible to produce paper drawings of every part, and to exchange and update design information in an efficient way. To increase productivity, minimize errors, and reduce process flow time, it becomes necessary to create a "paperless" environment. The emergence of CAD software accomplishes these by allowing rapid creation and communication of three-dimensional digital representations of the design features. Since every component in an airplane has the potential to affect every other component, CAD gives the designers and engineers freedom to experiment and evaluate design changes quickly and inexpensively. The second challenge is related to the efficiency of the traditional airplane design process within a large and highly compartmentalized aircraft company. The sequential nature of the traditional conceptual, preliminary, and detailed airplane design process tends to result in a long product development time. The top-down process usually involves the customer providing requirements, the program office developing guidelines, and the design office creating and evaluating concepts. The design is subsequently "frozen" and passed down to the production and manufacturing offices. In order to find the best and most economical way to realize the product, changes are usually needed that will affect all disciplines to modify the design, and the process repeats itself until a best possible compromise is reached. While this process might work well when the organization is small and interaction between design and manufacturing intimate and frequent, it can lead to undesirable delays in large organizations. Using information technology such as computer aided manufacturing and production can effectively restore close interaction and communication among a large number of people in the design process. In a computer assisted environment, the airplane designer has access to manufacturing processes and tools in the form of virtual environments. These will allow the designer to virtually manufacture the product while designing it. A more optimal design trade and resource allocation between production and airplane performance can be achieved early in the design stage.

We conclude this section by presenting some statistics from the study of the digitally designed Boeing 777 which demonstrate the great benefits from design automation achieved through CAD system. Boeing used CAD systems that combined geometric modeling using CATIA, finite element analysis using ELFINI (Finite Element Analysis System) and digital assembly using EPIC (Electronic Preassembly Integration on CATIA). The CAD systems allowed Boeing engineers to simulate the geometry of an airplane design on the computer without the costly and time-consuming investment of using physical mock-ups. More than 3 million parts were represented in an integrated database. A complete three-dimensional virtual mock-up of the airplane was created. This allowed the designers to investigate part interferences, assembly interfaces and maintainability using spatial visualizations of the aircraft components. In comparison with the earlier aircraft design and manufacturing processes, Boeing eliminated more than 3000 assembly interfaces without any physical prototyping, and achieved 90 percent reduction in engineering change requests, 50 percent reduction in cycle time for engineering change request, 90 percent reduction in material rework, and 50 times improvement in assembly tolerances for fuselage. Overall, CAD/CAM systems and digital pre-assembly greatly improve the quality of airplane designs and reduce the time required to introduce new airplanes into the marketplace.

6. Conclusion

The external appearance of long range commercial aircraft has not changed much during the last 50 years, reflecting the qualitative understanding of swept wing design that had been achieved by Kuechemann and his peers. The design process, however, has been completely revolutionized during the same period by the systematic use of computational simulation. Moreover the role of information technology now extends well beyond the design and manufacturing process to the actual flight operations and management through technologies such as digital fly-by-wire. These trends will inevitably continue. On the design side a major current challenge is in aero-acoustics, paced by the demand to reduce the noise signature of both take-off and landing operations. The prediction of airframe noise due to high lift systems and landing gear remains intractable with current computational methods, and will probably require a combination of higher order numerical algorithms with massively parallel computation. On the operational side there is tremendous interest in autonomous unmanned air vehicles (UAVs) for military operations. While it is doubtful whether passengers will be willing to accept the idea of flying in UAVs, one can imagine their adoption for cargo operations if the issues of their integration into the air traffic control system can be satisfactorily resolved.

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