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Going Supersonic
- from aeroplanes to cars!

Professor Nigel Weatherill

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Inaugural Lecture

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by

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Professor of Civil Engineering

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UNIVERSITY OF WALES SWANSEA

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Going Supersonic

- from aeroplanes to cars!

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Abstract

Man has always had a desire to travel at high speed. In 1904, a speed of 103mph held the world land speed record. In 1997, it is possible to fly on Concorde at twice the speed of sound or 1350mph. This paper discusses some of the historical landmarks of Man's quest for speed before detailing some related technical challenges. To help meet the ever-present demands for more efficient travel, new technology in the form of computer simulation, has been applied to simulate airflow over aeroplanes. The basic ideas underlying this new discipline are presented together with real world examples to which the technique has been applied. The paper concludes with a discussion on how this new computer technology is contributing to an attempt to develop the first supersonic car.

Introduction

Man has never been content with his own physical capabilities. From an early stage in evolution, Man has had to turn to machines to help him satisfy his curiosity for high speed travel. In the limit, this has manifested itself in the form of modern jet transportation which has changed the world in which we live and changed the way Man now views his environment.

It is not the social, economic or political issues of the consequences of the quest for speed which are of interest to us here. Instead, we will concentrate on some aspects of the technology which underpins Man's attempts to conquer speed.

Of course, it would be impossible to cover all aspects of technology which form the framework for high speed travel. Hence, I have chosen to concentrate on an emerging technology which is increasingly influencing the process of not only aircraft design, but more broadly, all engineering design.

Computers have evolved to a position where they now provide an essential tool for society. From word processing to virtual reality the spectrum of applications is wide. I want to focus here on their role in helping to assist aerospace design; more particularly, to discuss, through the example of high speed travel, the new discipline of computational engineering for which the Department of Civil Engineering is internationally renowned for its pioneering research and for which I have provided a personal, although modest, contribution.

The paper is structured into 4 parts. Firstly, an introduction which will provide an historical background into Man's quest for speed; secondly, an overview of some of the technical issues related to the aerodynamics of high speed travel, followed by a section which will describe the process of computer simulation. Finally, an outline will be given on how computer simulation will help push the world land speed record to over 800mph.

1. The early days

From the earliest days, Man has risked life, spent millions, and progressed technology simply to travel ever faster, on land, on water and in air.

1904	Louis Rigolly	France	103mph
1927	Sir Henry Seagrave	Britain	203mph
1935	Sir Malcolm Campbell	Britain	301mph
1964	Donald Campbell	Britain	403mph
1965	Craig Breedlove	USA	600mph
1983	Richard Noble	Britain	633mph

The history of the land speed record

Nicolas-Joseph Cugnot of France is considered to have built the first true automobile in 1769. The vehicle, which was designed as an artillery carriage, was a steam-powered tricycle capable of carrying four passengers for 20 minutes at 2.25 mph.

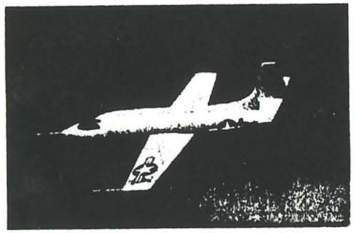
Automobile racing began soon after the invention of the gasoline- (petrol) fuelled internal combustion engine in the 1880s. The first organised automobile competition, a reliability test in 1894 from Paris to Rouen, was over a distance of 20 miles which was won with an average speed of 10.2 mph. By 1904, advances in technology had taken the land speed record to 103 mph.

In the air, the same is true. As flight became more routine, the desire to reduce travel times between cities and countries, or the requirement to out-run an enemy, provided the impetus for aerospace engineers to advance Man's capabilities in the sky.

1903	Wright "Flyer"	USA	11mph
1928	Gloster VI Sea-plane	Britain	336mph
1947	Bell X-1	USA	800mph
1965	Concorde	UK/France	1350mph
1971	SR-71 Blackbird	USA	2200mph

Major landmarks in the evolution of flight

A major landmark occurred in 1947 when Chuck Yeager, an American test pilot, was the first man to travel at a so-called supersonic speed in the Lockheed Bell X1. Painted orange so that it could be seen from the ground and named after his wife 'Glamorous Glennis', the aircraft penetrated the sound barrier accompanied by violent vibrations and buffeting which had previously destroyed other aircraft and in the process killed several test pilots.



Bell X-S (XS-1 eXperimental Sonic-1)

Chuck Yeager with 'Glamorous Glennis'

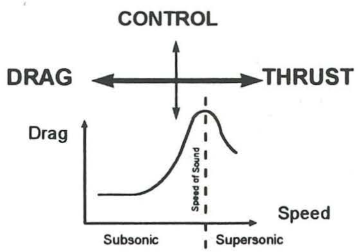
In 1965, the maiden flight of Concorde heralded the era of commercial supersonic travel. The characteristic shape of Concorde clearly identifies it from other aircraft. Slung beneath it in two box-like structures are four Rolls-Royce turbojet engines, capable of producing 69,000 kilograms of thrust. Nearly 130,000 litres of fuel are stored in wing tanks. At its cruising altitude of 15,000 metres, Concorde's aluminium skin reaches temperatures of 120 Celsius, and the fuselage stretches 10 centimetres causing the windows to shift slightly. Looking forward from the flight deck, the pilot sees the horizon 500 kilometres away; the view is 270 degrees, spanning 650,000 square kilometres. Inside the 100 or so passengers sip champagne and eat caviar while they cruise at twice the speed of sound or faster than a bullet fired from a gun!

It is easy to forget or perhaps more accurately, take for granted, the technology which surrounds us today. Imagine a few decades in the past, the concept of checking-in at Heathrow airport, waiting in the lounge and then boarding a vehicle which would carry you at over 1350mph from London to New York in 3½ hours. This concept must have been remote to Chuck Yeager as he took the Bell X1 in a nose dive from 35,000ft and was so violently shaken that there was a good chance of him and the aircraft disintegrating. Furthermore, he might well have doubted the mental sanity of anyone who would also pay over £3,000 for the privilege. Today, supersonic flight, given the money, is so routine each of us can experience travelling faster than a bullet. Perhaps equally impressive, but perhaps with not quite the same mystique, is a jumbo jet carrying almost 400 passengers long-haul distances around the world. Although not travelling faster than the speed of sound, as we will see, supersonic airflow also plays its role. Certainly, a lot has happened since the early days of Chuck Yeager.

2. Technical challenges

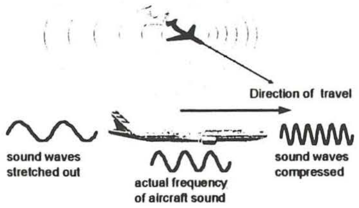
Central to all the advances which have brought Concorde and other supersonic aeroplanes to relative maturity is a good understanding of the key issues of the problem. In this case, these can be identified as power, aerodynamics and materials. Here, issues related to aerodynamics will be considered.

To travel at high speed it is necessary to create thrust, to overcome drag, whilst maintaining control. The relationship between these is complicated. It is clear from the relationship between drag and speed that something dramatic occurs around the speed of sound. To understand what is taking place, it is necessary to consider the physics of sound waves.



Thrust and drag must be in balance for control. The relationship between speed and drag shows that the speed of sound is special.

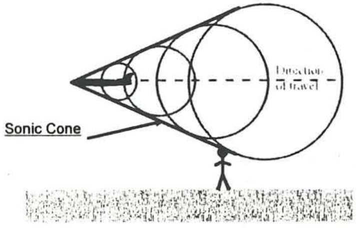
We are all familiar with the common phenomena of a police car moving passed with its siren blazing. We hear the familiar high pitch sound as it approaches and the lower sound as it moves away. This is the phenomena called the Doppler effect, named after the Austrian physicist Christian Doppler (1803-1853). We can ask the interesting question as to what happens if the police car were to be travelling at a speed close to that of sound itself.



The Doppler effect associated with aeroplanes

Since we don't at the present time have supersonic police cars, the question should be rephrased - what happens when an aeroplane, creating a disturbance in the form of sound waves, moves forward at a speed close to that of the speed at which sound travels? The sound waves ahead of the aeroplane are compressed and the wave length decreases, whilst behind the aircraft the waves are elongated. Since the pitch of sound is related to the wavelength and frequency of sound waves, then clearly the sound in front of the aeroplane is going to be different from the sound behind the aeroplane.

As the speed of the aeroplane moves towards and then passed the speed of sound the sound waves created by the aeroplane catch-up with each other to form a surface of compressed sound waves. Such a surface is called a 'shock wave'. Across a shock wave, there is a jump or discontinuity in physical properties, such as pressure and density. As the shock wave meets the ground it is heard as a bang - a result of the difference in pressure in front of and behind the shock wave. Associated with this wave is a rapid increase in the drag which a body experiences.



The waves created by a body which travels at supersonic speeds coalesce to form a shock wave. The boundary of the shock wave is called the Mach cone. It is the shock wave which gives rise to the sonic boom on land.

It is apparent from this explanation, that you do not hear an aircraft approaching at a supersonic speed. The aircraft is keeping up with the sound which conventionally indicates its impending arrival.

Ernst Mach (1838-1916)

Early studies on the movement of sound were undertaken by several famous scientists and engineers. The ratio of the speed of an object to that of the local speed of sound is given the special name of the Mach number after the famous scientist, Ernst Mach. The term 'local' is used because the speed of sound varies with local ambient conditions, such as, for example, temperature and density of air. At sea level the speed of sound is around 750mph.

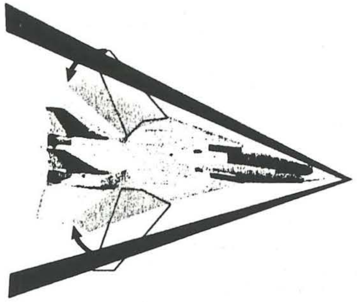
Given the appropriate atmospheric conditions, the jump in pressure across a shock wave can give rise to condensation which can be visualised like a cloud. It is rare to see such a phenomena, although it is occasionally witnessed by fighter pilots flying in formation.

The F14 Tomcat is seen to burst through the sound barrier.

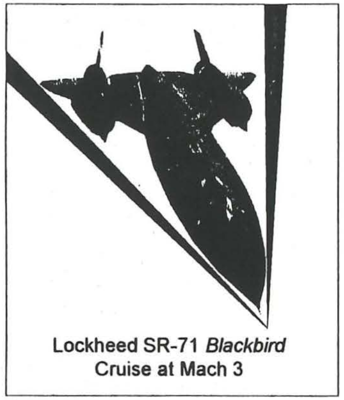
The barrier, a normally invisible wall marking the speed at which the compressed air piling up ahead of the plane creates a sudden, massive increase in drag, reveals itself and seems to stretch with the impact of the jet's nose cone. A vaporous radiance appears - the apparent barrier tears open, repairs itself in an instant and is gone.

Even with this level of understanding of the physics associated with the speed of sound, it is possible to begin to determine what consequences there would be in designing a supersonic aeroplane.

The nature of the shock wave which forms around an aircraft has a major impact on the shape an aircraft should take if it is to travel close to or above the speed of sound. If the wings penetrate the formed shock wave then the large differences in pressure give rise to buffeting - the effect which resulted in some early aircraft disintegrating with the loss of the aircraft and pilot. Hence, for smooth and efficient flight, the wings must be swept back inside the shock wave surface which is technically known as the Mach cone. This requirement, therefore, gives rise to the characteristic look of supersonic aircraft, such as Concorde. Unfortunately, the swept wing does not perform well at low speeds. This contradictory requirement has lead to the development of some aircraft which have so-called swing wings - small or no sweep for low speeds and high sweep for high speed flight.



The swing wing of the F14 Tomcat



The highly swept rear mounted wings of the SR-71 Blackbird

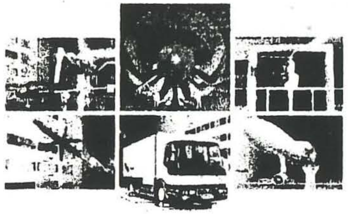
In the early days of development of aeroplanes for high speed flight, engineers had access to fairly basic design tools, such as wind tunnels, Schlieren photographs, the slide rule for calculations and elementary theory.

- WIND TUNNEL
  - *to provide measurements*
- SCHLIEREN PHOTOGRAPHS
  - *to provide visualisation*
- ELEMENTARY THEORY
  - *for predictive capabilities*
- SLIDE RULE
  - *to perform calculations*

Techniques and tools used to help understand high speed motion

Wind tunnels have been used for more than half a century. Primarily, low speed wind tunnels had been used since it was practical to drive air around some closed circuit at relatively low speeds. The idea of generating airflow, with the use of compressors, at a speed of 600 mph or more was unrealistic.

Wind tunnels vary in size. Some are full size, although this is clearly rare for aircraft which can, in the case of a Boeing 747, measure 75 metres from wing tip to wing tip. More common are wind tunnels with a working section, within which the aircraft is placed, of the order of several feet. Model aircraft, scaled in proportion to the real vehicle, with tiny holes and tubes in the surface from which the pressure on the surface can be measured, are built to amazing accuracy. A typical high quality model can cost over £100,000 and an hour in a wind tunnel can cost in excess of £10,000.

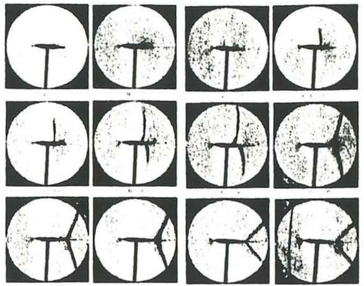


Wind tunnel testing

To create supersonic airflow in a wind tunnel, two states of air are created; one at high pressure and one at low pressure separated by a line diaphragm. The diaphragm is punctured and the air rushes at supersonic speeds from the high to low pressure. For a fraction of a second, the flow is supersonic and measurements can be taken of the aerodynamic characteristics of the model aircraft.

It is possible to capture the effects of supersonic airflow using very special camera technology. Schlieren photography allows the visualisation of density changes, and since the density of air changes through a shock wave, it also provides a mechanism for photographing shock wave patterns.

It is similar, to some degree, to the mirage effect commonly seen in summer on tarmac roads - air close to the road heats at different rates giving rise to differences in density and the light is then refracted, often reflecting the sky. Schlieren techniques have been used for decades in laboratory wind tunnels to visualise supersonic flow about model aircraft. The limitations, therefore are closely related to those of the wind tunnel.



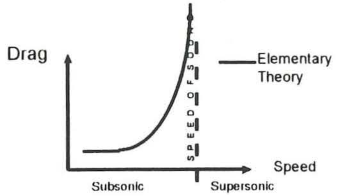
This array of Schlieren photographs shows different shock wave patterns for various air speeds over a wing section held in position by a sting

An alternative to experimentation is theoretical studies - arguably the key to an in-depth understanding. The theoretical study of the motion of air has been a topic of interest for over two centuries. However, as we shall see, the mathematics required for an in-depth understanding is extremely complicated.

Any approximations, or mis-interpretations of the physics can be misleading. There is the famous D'Alambert paradox. Jean Le Rond D'Alambert (1717-1783) was a famous French mathematician and philosopher who made major contributions in many branches of mathematics including fluid mechanics. In a treatise published in 1752 he considered air to be an incompressible elastic fluid composed of small particles and, drawing on knowledge from solid mechanics, took the view that resistance is related to loss of momentum of the particles on impact with moving bodies.

From his subsequent analysis he deduced the surprising result that the resistance of a body moving through air i.e. the drag, is zero. D'Alambert was himself dissatisfied with the result but it became known as D'Alambert paradox since the theory clearly did not agree with physical observation.

In a more general way, early contributions to theoretical aerodynamics were restricted and made limited contributions to our understanding of supersonic flight. Basic theory, in fact, showed that at the speed of sound, the drag would be infinite!



Limitations of elementary theory show the drag becoming infinite at the speed of sound

Although these techniques, with the exception of the slide rule, are still in use today, their limitations have motivated an investment in effort to develop new technology which can overcome some of the problems inherent to the older technologies discussed. One such technology which has been developed in recent years is the use of computers to simulate physical phenomena. How can computers help us reveal the secrets to efficient and safe high speed travel? To answer this question it is necessary to go back to the times of Sir Isaac Newton(1642-1727).

3. Computer simulation

The laws which govern the motion of air are derived using principles known and attributed to Newton. Mass must be conserved, as must momenta. Energy may change its form but it too is also conserved.

- **Conservation of mass**
  "Mass contained in a material volume does not change as the volume moves with the flow"
- **Conservation of momentum**
  Newton's second law of motion
- **Conservation of energy**

The fundamental laws of physics

These physical principles can be expressed in mathematical form. For air this was done in the 1700s by a French mathematician, Navier and the famous British scientist Lord Stokes. The name given to the governing equations is, therefore, the Navier-Stokes equations. Amazing as it may seem, these equations govern all airflow - the motion of air driven by ventilation fans through to the motion of air over an aircraft travelling at supersonic speeds. The equations are complicated!!

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}=0$$

$$\frac{\partial \rho u}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=-\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$

$$\frac{\partial \rho v}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=-\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$

$$\frac{\partial \rho w}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=-\frac{\partial p}{\partial z}+\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

$$\frac{\partial \rho E}{\partial t}+\frac{\partial(\rho uE)}{\partial x}+\frac{\partial(\rho vE)}{\partial y}+\frac{\partial(\rho wE)}{\partial z}=-\frac{\partial pu}{\partial x}-\frac{\partial pv}{\partial y}-\frac{\partial pw}{\partial z}+S$$

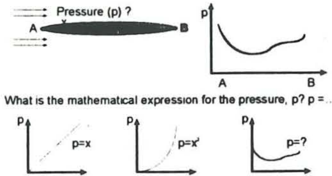
The equations which govern the motion of air - the Navier-Stokes equations. They represent a balance between advective and diffusive effects.

To a non-mathematically minded individual they appear to be gobbledegook! However, like any equation we seek values which when substituted into each term of the equation produces a balance.

These equations which have been around for over 200 years have still not been solved in their general form using conventional mathematics. Technically, we call the equations non-linear partial differential equations. However, embedded in the equations is the solution to perfect supersonic flight and the complete description of the motion of air.

Let us look at the problem of the solution of these equations in more detail.

How do we face this apparent intractable problem - a set of equations not solved in over 200 years using mathematical methods. Let us consider the problem in stages. Assume that we would like to describe the behaviour of the pressure along a curve which we will describe as starting at A and finishing at B.



The behaviour of the pressure cannot always be described in a neat conventional form.

If the pressure varied so-called linearly with distance *x*, then we could say that

$$pressure = ax,$$

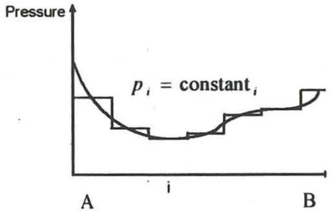
where a is any constant. If the pressure behaved in a quadratic relationship with distance x then we could write

$$pressure = bx^2$$

where b is any constant.

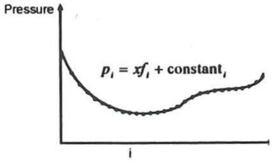
However, what do we do when the pressure varies in a non-standard way with the distance? We can no longer write that the pressure varies in some nice neat form like the two previous relationships. Without doubt, the unknown variables in the Navier-Stokes equations will vary in a non-standard way. So what do we do? Like any good engineering approach we initially simplify the problem.

The behaviour of the pressure with distance x is complicated. Hence, let us subdivide the interval between A and B into sub-intervals. Within each sub-interval let us assume that the pressure is constant. This gives us a reasonable approximation to the curve. If we subdivide the interval A to B into more sub-intervals then, clearly we obtain a still better fit to the complicated shape of the curve.



The shape of the curve is approximated by sub-dividing the interval into smaller sub-intervals. Within each sub-interval, the curve is assumed to behave in a simple form.

We can go one stage further and not only assume that the interval A to B is subdivided into many sub-intervals, but that within each sub-interval the pressure varies linearly with the distance. Now, given a reasonable number of sub-intervals, the fit between the initial curve and the collection of straight lines within each sub-interval is quite good - certainly good enough to describe the shape of the curve to a reasonable degree of accuracy. Anyway, if we wish for greater accuracy we can always increase the number of sub-intervals.



Assuming a linear variation within each element the approximation to the curve is more accurate

Although elementary in character this basic procedure is at the heart of the Finite Element Method. Each sub-interval is called an ***element*** which covers a ***finite*** interval. Within each element an assumption is made about how the unknowns, i.e. the quantities which we need to find, vary.

Extending these ideas to 2 and 3 space dimensions is, in principle, the same. Regions in two dimensions are subdivided into elements of triangles or quadrilaterals, whilst for three dimensions, elements based upon tetrahedra (volumes with 4 triangular faces) or hexahedra (volumes with 6 quadrilateral faces) can be used. The unknown quantities, such as pressure, are again assumed to change within an element in a very simple way, for example, are constant or change linearly, within an element.

Given this simple form of the representation of each unknown variable within a sub-interval (or element), it is possible to substitute this form into the governing Navier-Stokes equations. This has the effect of converting a small number of very complicated equations into many simple equations. In fact, there may be the same number of equations as there are elements.

The resulting equations are often in a simple form. For illustrative purposes, let us assume that they reduce to a system of simultaneous equations. They are easy to solve - in fact, so easy to solve that we can ask the computer to perform the task for us. Let us look at what task we would like the computer to perform.

After substituting the form of variation within each element into the Navier-Stokes equations we may obtain equations like

$$p_1 - p_2 = 4 \,.........(1)$$

$$p_1 + p_2 = 8 \,.........(2)$$

where p_1 and p_2 are the pressure in elements 1 and 2.

We need to solve these equations p_1 and p_2. To achieve this, we can use an elimination method. Adding equation (1) to equation (2) eliminates p_2 to give

$$2p_1 = 12$$

and thus

$$p_1 = 6$$

Since we now know p_1 we can substitute this into equation (1) to give

$$6 - p_2 = 4$$

and thus

$$p_2 = 2$$

This way of solving equations is called Gauss elimination after the famous German mathematician Johann Friedrich Gauss (1777-1855). It is easy to write down in a systematic way each of the steps required to solve the simultaneous equations. It is then straightforward to write a computer program which will tell the computer how to solve a given set of simultaneous equations. In general, for a realistic problem, we will have hundreds of thousands, perhaps millions of equations - but the computer is good at repeating simple tasks many many times over.

What has been described is the so-called finite element method. After the formal mathematical manipulation of the problem there is a requirement to perform a lot of computations. This is where the modern computer plays an essential role.

The Finite Element Procedure

1) Define the geometry of the shape of interest by a set of points
2) Sub-divide the region around the geometry into a set of elements (e.g. triangles, tetrahedra)
3) Make assumptions as to how the unknown flow variables (e.g. velocity, pressure) vary within each element (e.g. constant, linear)
4) Derive the 'simplified' equations within each element
5) Solve the equations on a computer
6) Using computer graphics, display the results

In the early development days of the finite element method, computers were not widely available and, furthermore, their capabilities to be programmed with a set of instructions were primitive. Initial computations were, in some establishments, carried out by teams of individuals using calculating machines.

The history of computers strictly dates back over 5,000 years to the abacus which was used widely in the Orient. Mechanical calculating machines were invented in Europe during the 17th century. The first such device was an adding machine built in 1642 by the French scientist Blaise Pascal. The first automatic digital computer was conceived in the 1830s by the English inventor Charles Babbage. Called the Analytical Engine, this mechanical device was designed to combine arithmetic processes with decisions based upon its own computations. Interestingly, Babbage's machine was never completed and his work was forgotten until his writings were rediscovered in 1937. In 1944, collaborators in the US, involving International Business Machines Corporation completed the Automatic Sequence Controlled Calculator, commonly known as Harvard Mark 1. It was an enormous machine , approximately 50 feet long, and eight feet high. Since this development, the digital computer has evolved at an extremely rapid pace. The succession of advances in computer hardware is generally discussed in terms of the concept of generations.

Interestingly, a First Generation computer was completed in 1946, just one year before the flight of Chuck Yaeger. ENIAC(Electronic Numerical Integrator And Calculator) was the first all-purpose, all electronic digital computer. ENIAC was more than 1,000 times faster than its electromechanical predecessors and could execute up to 5,000 arithmetic operations per second.

Today, in the age of the Fifth Generation of computers, the speed at which computers can perform tasks, in particular, mathematical operations such as add, multiply and divide, has reached unimaginable proportions.

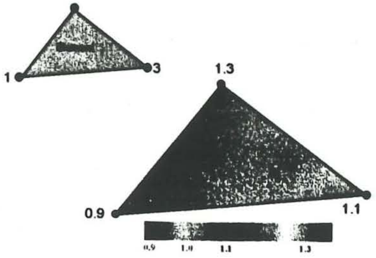
One of the first computers to be generally available was the famous Sinclair ZX-81 developed by Sir Clive Sinclair and available in shops at a cost of around £100. At a similar time, to meet the requirements of scientific and engineering challenges, the CRAY supercomputer was available. Named after the designer, Seymour Cray, this machine was within the remit of large corporations and governments and had a price tag of around £2million.

The ZX-81 paved the way for the modern multimedia PC and with it the explosion of Microsoft, whilst the CRAY introduced the era of the 5th Generation of Computer, where the cost of some machines can reach over £20 million. Today, the trend is to make computers with more than one processor or more than one brain. Computers with hundreds of processors, all connected together and working in tandem, now provide the way to solve the emerging engineering problems of our age. With multiple processors, computers are now capable of staggering capabilities. The 8 processor CRAY YMP-EL 98, a 'baby supercomputer' which we have in the Department of Civil Engineering at Swansea is capable of 1.6 billion floating point calculations per second.

Clearly, computers, like most commodities, are designed to meet the demands of the market place. A walk through a research room of a University department will indicate that there are computers which try to encompass a little of all - they are commonly referred to as the Computer Workstation. These are machines which have a good price/ performance capability and are priced so that most researchers can have one sitting on their desks. These machines enable the researcher to develop computer programs, test-out ideas, perform computations and display the results.

Such a machine is the Silicon Graphics Indigo workstation. Capable of about 1 million floating point operations per second (1 MFLOP - 200 times more powerful than the 1946 ENIAC) it also contains impressive capabilities to perform computer graphics. With over 32 million colours at its disposal, it is well suited to presenting the millions of numbers which typify an engineering computer simulation.

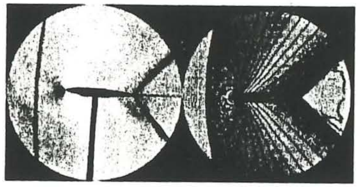
The basis of the colour graphics is straightforward. Given 3 nodes of a triangle, where each node is given a colour, the triangle can be colour shaded by blending the colours associated with each node. Each pixel inside the triangle is automatically given an appropriate colour by the computer.



Computer colour graphics

The result is a smoothly varying colour shaded triangle. In the spirit of contour plots, it is easy to colour code the data from our computer simulations so that the millions of numbers associated with a computation, can, in an instant, be presented in a meaningful manner.

Let us review our approach to computer simulation. The finite element method provides us with a way to reformulate the complicated equations which describe the flow of air into many simple equations and the modern computer, provides, firstly, a tool to perform the millions of calculations and secondly, a way to present the results of the calculations in a way which is easy to understand.



The comparison of a Schlieren photograph and the contours obtained from a computer simulation show good agreement. This picture compares supersonic flow at Mach 1.2 over the section of a wing.

So how accurate are computer simulations of the type just discussed? We can compare the results from a Schlieren photograph with those obtained from a computer simulation.

In general, we can obtain good agreement for certain types of flow. However, much still remains to be done on the accuracy of computer simulations for complex airflows which involve rapid fluctuations typical of turbulent flow.

Using the ideas described above, it is clear that computer simulation provides a relatively cheap and efficient way of investigating the aerodynamics of aircraft. No highly expensive models are required and no expensive wind tunnel testing, only computer generated geometries. The shape of components such as wings can be modified in a matter of minutes and new computations performed in a matter of hours. Aerodynamicists can explore new and innovative shapes and design concepts without expensive wind tunnel or flight tests.

Computer simulation is now routinely used throughout the world-wide aerospace industry. The major benefits relate to cost effectiveness and helping to meet stringent design targets within the project deadlines.

It is apparent from the above discussions, that computer simulation of engineering problems is a truly multidisciplinary science. It requires aspects of mathematics, computing, physics, and engineering.

The Design of the A330/A340 AIRBUS

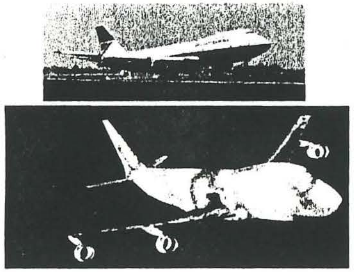
Stringent design targets :
10% reduction in cruise drag cf. A310
33% reduction in cruise drag cf. MD11
CFD design :
800 different wing geometries calculated
Time : 2 years
Cost : £500,000
Wind tunnel design (projected) :
800 different wing geometries
Time : 150 years
Cost : £65,000,000

Computational methods are increasingly making a significant impact in helping design engineers to meet stringent design criteria.

Let us consider some typical examples of computer simulations over realistic aircraft.

Consider the airflow over a Boeing 747 in cruise conditions. The aircraft will be travelling at about 580 mph with respect to the ground. However, as the air accelerates over the wings, it reaches speeds in excess of that of the speed of sound - such a condition, where the aircraft is travelling slower than the speed of sound but air locally travels faster than the speed of sound, is called transonic flow. This is the regime where most modern jets operate and the design of efficient aeroplanes represents a severe challenge to aerospace engineers.

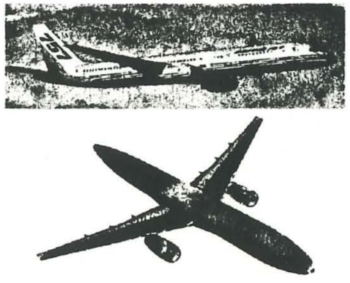
Up until the mid 1980's only simple models of fluid flow had been used to try and simulate the airflow over a Boeing 747. To that date, the necessary techniques required to solve the more difficult equations had not been developed. However, in 1985, the first computation was performed - it represented a major landmark. The computation was performed by a team of three British engineers (Jameson, Baker, Weatherill) working at Princeton University in America. Using a CRAY supercomputer, the region around the aircraft was subdivided into approximately 26,000 tetrahedra. Within each of these tetrahedra or 'elements' the equations governing the movement of frictionless air were solved. The computation predicted the supersonic flow of air above the wings of the 747.



A Boeing 747 with a computer simulation. The red colouring on the computer generated picture indicates supersonic flow. The aircraft is simulated to be flying at Mach 0.84 at 2.73 degrees to the freestream flow.

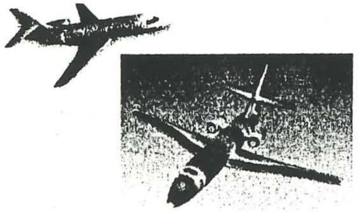
Today, the use of just 26,000 tetrahedra would be deemed to be too limited and with today's techniques 1,000,000 tetrahedra are routinely used to perform such computations. However, the calculation was deemed to be such a stepping stone that it deserved an article in the New York Times, together with other popular newspapers.

Typical of the times required to perform these calculations, the simulation of the flow over a Boeing 757 aircraft took 2 days of man effort to define the geometry and provide all the required calculation data and 2 hours to perform the computation on a CRAY supercomputer. Today, considerable research effort is being expended to reduce the overall times for the simulation still further.



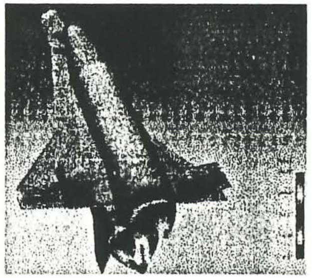
A Boeing 757 with a computer simulation. The red colouring on the computer generated picture indicates supersonic flow.

Another similar example is the simulation of flow over a Dassault Falcon executive jet.



A Dassault Falcon with computer simulation.

There is no real limit to the applications which can be studied using the computer approach. Consider the European Space shuttle. Designed to sit on the back of the Ariane rocket the shuttle, Hermes, like the American space shuttle, will return to earth at a speeds in excess of 10 times that of the speed of sound.



Surface velocity contours on the European Space Shuttle Hermes

At speeds beyond about five times the speed of sound (Mach 5), the term hypersonic flight is employed. How will it perform, will it be stable, will it burn-up as it bounces into the earth's atmosphere? Computer simulation can help in answering some of these questions.

So far we have just considered aerospace applications for this new technology. Traditionally, Man has always considered travelling faster than the speed of sound to be the domain of the flying machine. In the whole of the history of aviation, only three men have 'gone supersonic' without the benefit of an aircraft! In separate incidents, two pilots have bailed out of planes travelling at supersonic speeds and lived to tell the story. A third set a world record for the longest delayed parachute drop and went supersonic in the process. In 1960, Captain Kittinger of the US Air Force stepped out of a balloon at 103,000 feet and dropped 85,000 feet before deploying his chute. For an instant - in rarefied air at 90,000 feet - he was plummeting earthwards at a speed of 830mph, or Mach 1.25. However, all this may change if the present world and speed record holder, Mr Richard Noble, has his way.

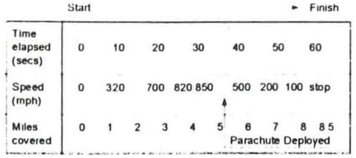
4. The Supersonic Car

In the next 12 months it is hoped that a fourth man will travel at a supersonic speed without the aid of an aircraft. Andrew Green, a trained RAF fighter pilot, hopes to drive a car, Thrust SSC (SuperSonic car) at a speed close to Mach 1.15 or 850mph. The car is basically two Rolls-Royce Spey engines strapped together. The power is awesome!

Vehicle	Power to weight ratio
VW Golf	66 bhp/ton
Lotus Esprit	155 bhp/ton
Formula 1 Car	755 bhp/ton
RAF Phantom	4167 bhp/ton
THRUST SSC	14287 bhp/ton

A comparison of the power of Thrust SSC

A comparison of the power to thrust ratio of Thrust SSC with other machines shows the impressive performance of the supersonic car. The profile of the dynamics of an attempt at achieving supersonic speeds by a car reveals the challenges posed to engineering design by the project. As a comparison for this profile, Concorde lifts off from the runway at 250mph and reaches the speed of sound, Mach 1, in 23 minutes.



Start ► Finish

Time elapsed (secs) 0 10 20 30 40 50 60

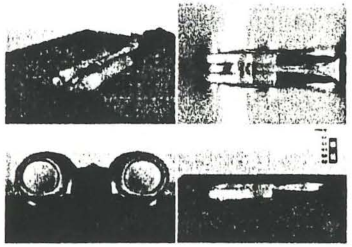
Speed (mph) 0 320 700 820 850 500 200 100 stop

Miles covered 0 1 2 3 4 5 6 7 8 8 5

A profile of the attempt to break the sound barrier.

How is such a car designed - it is novel, unique and, in engineering terms, is clearly well beyond the present envelope of design experience for cars!

Although an attempt at supersonic speeds has not yet been made, a quote from the Daily Telegraph reveals that at Swansea we have an insight into the problem. ***"Thrust SSC has already been driven in the heart of a computer in simulations conducted in the Department of Civil Engineering, University of Wales Swansea".*** The techniques which were initially developed to simulate high speed aircraft flight have been applied to the supersonic car.



Computer generated pictures of the pressure predicted on the surface of Thrust SSC

The process of solution is standard. Model the geometry of the car within the computer. Define a solid surface for the ground and a boundary at which disturbances from the car are small. Subdivide the space around the car into elements which, in this case again are in the form of tetrahedra. Within each tetrahedra make an assumption about the behaviour of the unknowns in the airflow. Reduce the very complicated Navier-Stokes calculations to hundreds of thousands of simple equations and solve on the computer. Process all the numbers to identify the required aerodynamic quantities such as drag, and lift (hopefully in this case not sufficient for the car to lift-off!) If required present the results using computer graphics.

5. Future challenges

Today passengers on board Concorde are pampered for over three hours as they speed across the Atlantic at Mach 2. Only military pilots and astronauts have ever flown faster - but without the comforts of leather seats and champagne. The Concorde fleet is ageing, but designers are developing commercial aeroplanes that can fly faster, further and higher. Armed with new technologies, such as computer simulation, companies like Boeing and McDonnell Douglas are actively pursuing the idea of high-speed civil transport (HSCT). Flight above Mach 3 poses new challenges. Since HSCTs would cruise above 60,000 feet, their engines must emit less nitrogen oxide than conventional jets so as not to harm the ozone layer. To be commercially viable, the new aircraft would require a range of 7,000 miles, twice that of the Concorde. Designers must also find ways of limiting the sonic boom in order to gain permission for supersonic flight over land.

Another challenge arises to carry over 800 passengers long haul distances around the world at speeds just below that of sound - an aircraft that would be twice the size of the Boeing 747!. British Aerospace is presently investigating the aerodynamics of such an aircraft. Probably with two decks, it will have to be aerodynamically efficient and hence designers will have to address the issue of supersonic flow and shock waves locally around the wings.

There is no question, given the rapid march of science and engineering, that these problems will be solved - and that airlines may one day in the not too distant future carry passengers between New York and Tokyo in around three hours and transport, in one aircraft, over 800 people from New York to London. If such ventures are funded, I hope that I have demonstrated, that computer simulation will have a major role to play in the success of these and many other projects.

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