ACCURIS

The ESDU VGK Toolbox

A Powerful Tool for Aircraft Design and Optimisation

Author: Dr D R Philpott

The ESDU VGK Toolbox

A Powerful Tool for Aircraft Design and Optimisation

Summary

The initial stages of aircraft design have a significant impact on overall project costs and timelines. For effective and precise predictions, it is essential to utilise methods that are both cost-effective and easily operated in a repetitive manner. Aerodynamic prediction tools for aerofoils are fundamental in the design of aircraft wings, propellers, and helicopter rotor blades. Consequently, there is a strong need for transonic, two-dimensional (2D) aerodynamic prediction codes that are quick, user-friendly, and suitable for optimisation studies across various applications.

The Viscous Garabedian Korn (VGK) 2D aerofoil method is widely utilised and validated. It demands fewer resources than Reynolds-Averaged Navier-Stokes (RANS) codes while delivering comparable accuracy in the normal operating range of an aerofoil. Nonetheless, the original VGK aerofoil method was cumbersome to use and, until recently, the run time with available computing hardware was too slow for heavy repetitive use. Recent advances in hardware have removed this problem; however, data entry and output processing still need to be faster and require less user expertise.

The ESDU VGK Toolbox Graphical User Interface (GUI) now provides an intuitive setup and immediate access to graphical and tabular results. As a result, it is an outstanding design tool appropriate for both the conceptual and preliminary design stages. Furthermore, it is a practical educational resource, enabling instructors and students to demonstrate and investigate the complexities involved in transonic wing design.

The Challenge of Modern Aircraft Design

The typical aircraft development process, from the initial definition of the mission to the final delivery, is illustrated in Figure 1. This process can take several years, making it crucial to reduce the timeline. Long design timescales and delays might lead to changes in the original mission requirements by the time of delivery, or competitors might introduce their products sooner.

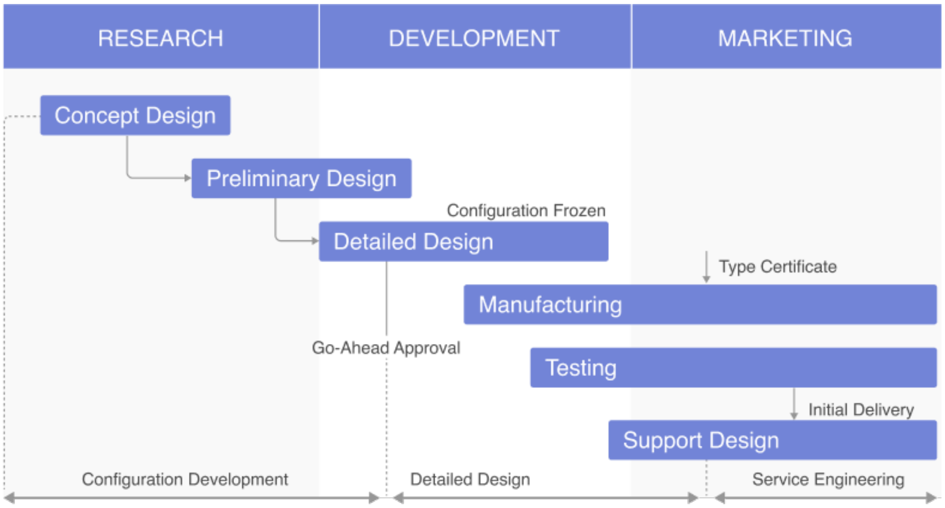

Fig. 1 The aircraft development process, from concept to delivery (taken from ESDU 21001)

An important commercial factor to consider is cost. Figure 2 illustrates the typical costs incurred at different stages throughout an aircraft's life, highlighting the portion of the total cost that becomes fixed based on decisions made at each stage.

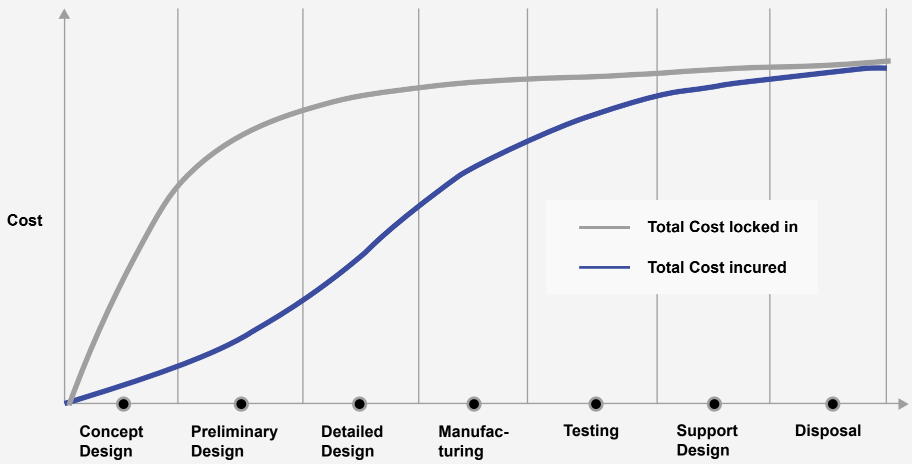

Fig. 2 Costs during the life of an aircraft, from concept to disposal (taken from ESDU 21001)

Despite the relatively low expenses incurred, the conceptual and preliminary design stages substantially impact total costs. Providing accurate and timely data during these stages can minimise the need for costly rework later and establish a solid foundation for the Go-Ahead Approval decision phase.

The design process demands cooperation between several disciplines, resulting in the need for easy-to-use prediction tools that allow rapid interchange of accurate data between the various specialist teams as the design evolves.

Aerodynamic prediction tools are essential in aircraft design. The ESDU 21001 Data Item, “Guidance on the Selection of Aerodynamic Methods to Use at Different Stages of Civil Aircraft Design,” provides a comprehensive review of readily-available aerodynamic prediction methods, suitable for general aviation and transport aircraft with cruising speeds up to the transonic range. ESDU 21001 identifies where each method is used in the overall design process.

The VGK aerofoil method is identified as being of primary use in the preliminary design stage and of limited use in the conceptual design stage for turboprop and civil transport aircraft. The introduction of the ESDU VGK Toolbox provides a user interface that permits both the rapid solution of multiple cases and reduces the need for user expertise. This reduces the time required for “what if” design studies and extends its use in both the conceptual and preliminary design stages.

Navigating the Future of Flight

The Role of 2D Aerodynamic Prediction

Since the introduction of the Boeing 707 in 1958, which benefited from the design experience gained from the B-47 bomber (1948), there has been a steady evolution in both engine and airframe design.

However, the basic configuration of commercial aircraft has remained largely unchanged, as shown in Figure 3.

In recent years, there has been increasing pressure to reduce carbon emissions, leading to proposals for alternative propulsion systems, such as electric engines for short-range aircraft and hydrogen fuel for long-range flights. Additionally, there have been suggestions for alternative configurations to enhance aerodynamic efficiency. This has sparked interest in conceptual and preliminary design studies of several unconventional configurations.

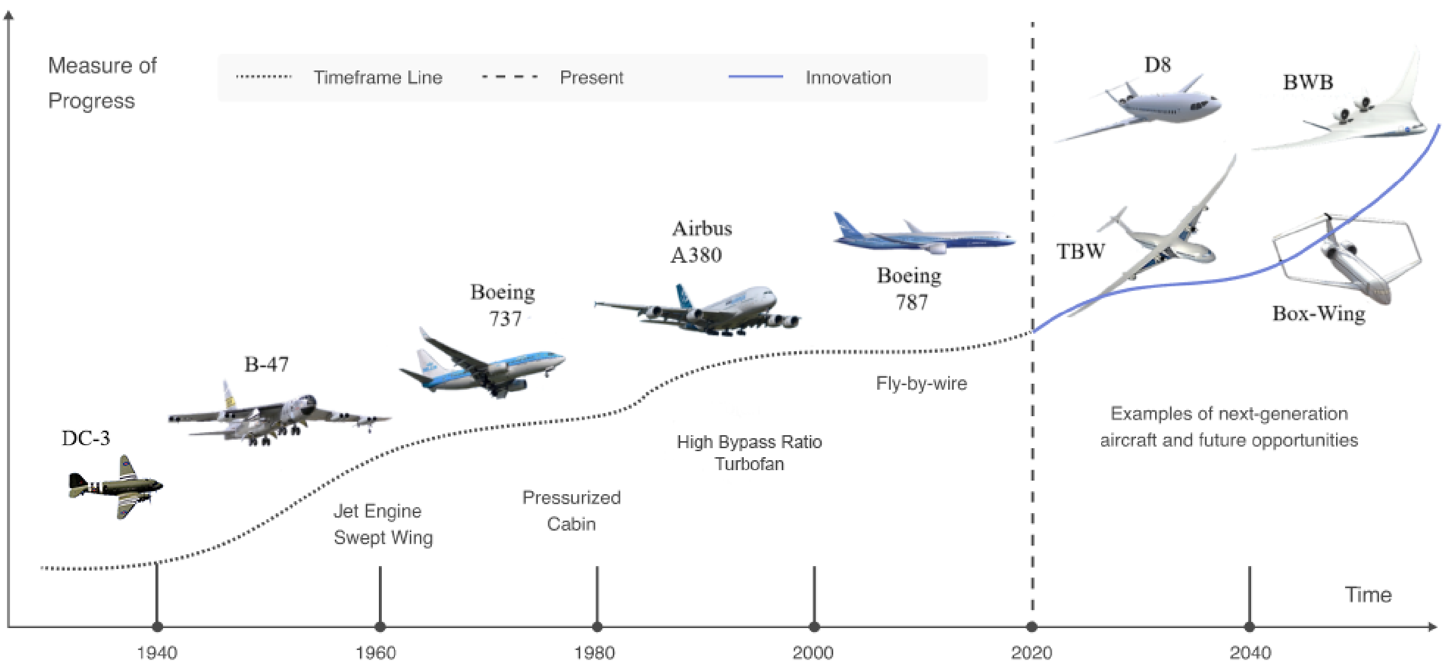

Fig. 3 Development of transport aircraft (taken from Progress in Aerospace Sciences Volume 131, 1 May 2022, 100813, Elsevier)

In its 2024 Global Market Forecast I Airbus states that 70% of the current air transport fleet will need to be replaced over the next 20 years to meet the goal of reducing carbon emissions. Whether these replacements involve unconventional designs or developments in conventional configurations, fast, reliable, and accurate aerodynamic prediction methods for 2D aerofoil sections will be crucial in the preliminary design process. Choosing a suitable method for unconventional configurations is especially important due to the limited data available from previous designs.

Transonic 2D aerofoil aerodynamic prediction methods are essential during the preliminary design stage in various industries and for educational purposes. These methods are also used in the design of propellers for transonic cruise and helicopter rotors. They have recently been applied to emerging concepts like air taxis as illustrated in Figure 4.

Fig. 4 Examples of a high-speed propeller and vertical take-off air taxi (airbus)

To effectively support all the applications mentioned, and to be suitable for preliminary design purposes, the chosen 2D aerofoil method should meet the following criteria:

- Cover a speed range up to transonic speeds, accommodating weak shock waves.
- Be efficient enough for repeated calculations needed for optimisation studies and responsive to changing constraints from other design disciplines, such as wing structure and fuel storage thickness requirements.
- Provide accuracy, be well-established, and validated through reliable methods.
- Be capable of running on a standard laptop or PC for accessibility.
- Be readily available for use.
- Be user-friendly and easy to set up, even for those without specialist knowledge of the prediction method.
- Offer quick access to both numerical and graphical results.

Unraveling the Complexity of CFD

From Theory to Practice

ESDU 21001 endorses Computational Fluid Dynamics (CFD) methods as an essential design tool for predicting the aerodynamic performance of 2D aerofoils. Below, we outline the physical principles that support these methods and discuss their suitability during the preliminary design phase.

CFD Methods

CFD methods can be divided into two main categories:

- **Dynamic methods** involve the simultaneous solution of three sets of differential equations: the momentum equation, which governs the production of momentum based on Newton's laws; the continuity equation, which ensures accurate accounting of the mass of fluid inflow; and the energy equation, which accounts for the interchange between kinetic and internal energies of the gas. Including the energy equation is necessary for compressible flows, where changes in density are significant.

- **Kinematic methods** do not rely on Newton's laws but depend solely on simple constraints, such as ensuring that the velocity is zero normal to solid surfaces, the flow returns to freestream conditions in the far-field and that the flow is inviscid (i.e. without viscosity).

Dynamic methods

The Navier-Stokes momentum equations for viscous flows were developed over two hundred years ago. However, due to the complexity of these equations and the need for very fine grids to resolve important flow details accurately, Direct Numerical Simulation (DNS) codes that solve the fundamental equations are often impractical for general use, even with the computational resources available today.

As a result, Reynolds-Averaged Navier-Stokes (RANS) codes have been developed. These codes reduce the computational resources required by incorporating semi-empirical turbulence models, eliminating the need to resolve detailed turbulent structures.

RANS codes can produce accurate results and are readily available. They often include user-friendly GUIs that assist in setting up calculations and examining the results, as shown in Figure 5.

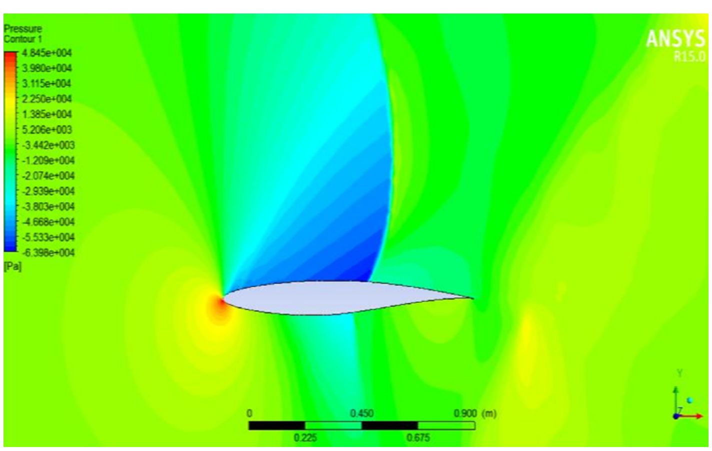

Fig. 5 RANS CFD Simulation of the RAE 2822 supercritical aerofoil at M = 0.8 using ANSYS FLUENT. International Journal of Research in Engineering and Technology eISSN: 2319-1163 pISSN: 2321-7308

Despite advancements, there remains a need for very fine grids in areas close to solid surfaces, and the solutions can be sensitive to the extent to which the grid extends into the far-field. This requirement and the need to solve a complex system of equations results in a time-consuming setup process, even for experienced users.

Additionally, it demands significant computational resources and long run times. As a result, RANS codes are generally unsuitable for preliminary design (ESDU 21001), although they play a crucial role later in the design cycle.

Kinematic methods

These methods were initially developed due to the challenges associated with solving the full equations of motion before the advent of computers. In their fundamental form, they are suitable for analysing 2D and 3D low speed flows, in which compressibility effects are negligible

The flow is also assumed to be inviscid, meaning that they do not predict drag. Within the normal operating range, viscous effects are important only in a thin boundary layer adjacent to the surface. Lift and pitching moment are predicted with good accuracy.

Once computers became more widely available, kinematic panel methods were developed and extensively applied to 2D and 3D flow analyses. The simplest example of a panel method is illustrated in Figure 6 for a 2D aerofoil. The surface is approximated using line segments, referred to as panels, with a point vortex placed at the center of each panel. The velocity normal to the centre of each panel is a combination of the velocities produced by the surrounding vortices and the freestream velocity. The strengths of all the vortices are determined by adjusting their strengths until the normal velocities are zero, ensuring that the flow exits smoothly at the trailing edge in accordance with the Kutta condition.

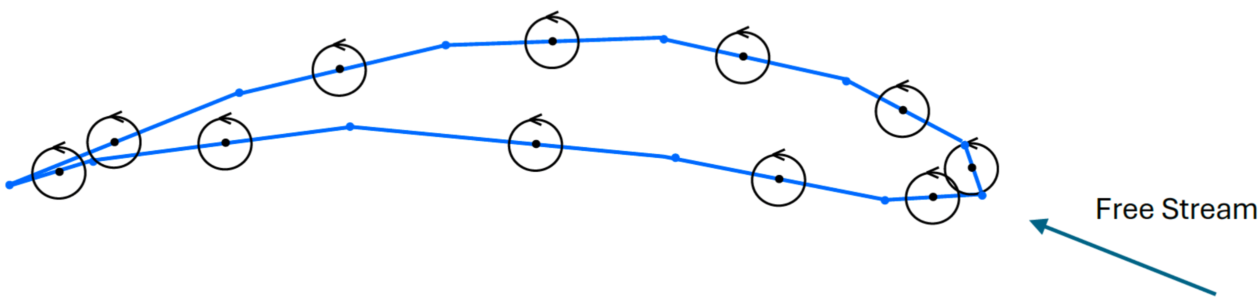

Fig. 6 A basic panel method for a 2D aerofoil

Mathematically, this process involves solving a set of linear equations, hence panel codes are typically straightforward to implement with short run times. However, as stated previously, drag is not predicted. This problem is overcome by coupling the kinematic model with a semi-empirical integral boundary layer method, which allows drag to be predicted with good accuracy. Such boundary layer methods are very reliable, well-established, and computationally inexpensive.

The Mach number range of a kinematic method is extended by incorporating a compressibility correction factor, such as the Karman-Tsien compressibility correction used in the well-known XFOIL 2D aerofoil program. This factor depends solely on the freestream Mach number, maintaining the advantages of linearity, which contributes to speed and simplicity. However, the accuracy of these methods deteriorates rapidly when the local Mach number approaches 1 anywhere in the flow field, which often occurs with freestream Mach numbers above approximately 0.4. This limitation prevents using these methods as a design tool across the Mach number range typical of many transport aircraft.

The VGK Aerofoil Method

The original kinematic method was developed by Garabedian and Korn in the 1970s. It was enhanced to include drag prediction by coupling it to an integral boundary layer method, resulting in the VGK aerofoil method. After extensive validation, this method was published in the ESDU Transonic Aerodynamics Series in October 1996. The VGK aerofoil method[1] is specifically designed for the analysis and design of aerofoils operating at transonic Mach numbers, and is widely used in practice.

In the VGK aerofoil method, the Mach number range is extended by utilising a compressibility factor that varies according to the local conditions throughout the flow field. This prevents the use of the simple flow elements typically employed in panel methods and necessitates the solution of a non-linear differential equation for the velocity potential, the gradient of which provides the local velocity components. As a result, run times are significantly shorter than those of RANS methods but longer than those associated with linear kinematic methods.

Gridding the entire flow field is necessary; however, the very fine meshes near solid surfaces needed in RANS codes are not required. In the VGK aerofoil method, flow calculations are conducted on a circular grid, where the circumference represents the aerofoil surface and the centre corresponds to the freestream located infinitely far away. This setup ensures that the solutions reflect "free air" conditions and are not influenced by the grid's far extent, a common issue in RANS codes. The grid is common to all aerofoils and is automatically generated at run time by applying a conformal transformation to the supplied aerofoil coordinates. This requires no user intervention and eliminates the need for the extensive involvement of a skilled user, which is often necessary for grid development in RANS.

When ESDU published the VGK aerofoil method in 1996, it could be run on a desktop computer. However, the absence of modern GUIs, and significant run times of around 20 minutes, limited its use during the critical preliminary design stage and as an educational tool. Subsequent developments have significantly reduced run times to just a few seconds.

The ESDU VGK toolbox GUI now allows users to set up the program and display results quickly.

Footnote: [1] Developed over a period of years at RAE/DERA (now Qinetiq), the VGK aerofoil method is made available by Accuris (ESDU) under the terms of an agreement with Qinetiq. Crown copyright is retained in the VGK source code.

ESDU VGK

A Powerful Toolbox for Efficient Aerofoil Design

Input and output

The ESDU VGK Toolbox allows quick input data setup and presents results in graphical and tabular formats for easy viewing and export. Several calculation options are available, such as inviscid or viscid calculation, and solutions can be obtained at a specified lift coefficient or angle of incidence.

Here the most commonly used option, viscous solutions at specified incidence angles, is described.

The user must initially load a table of aerofoil coordinates either by selection from the library provided or by loading a user-supplied coordinate file. The aerofoil profile is then displayed in the GUI, as shown in Figure 7. The coordinates can also be viewed and edited in a table.

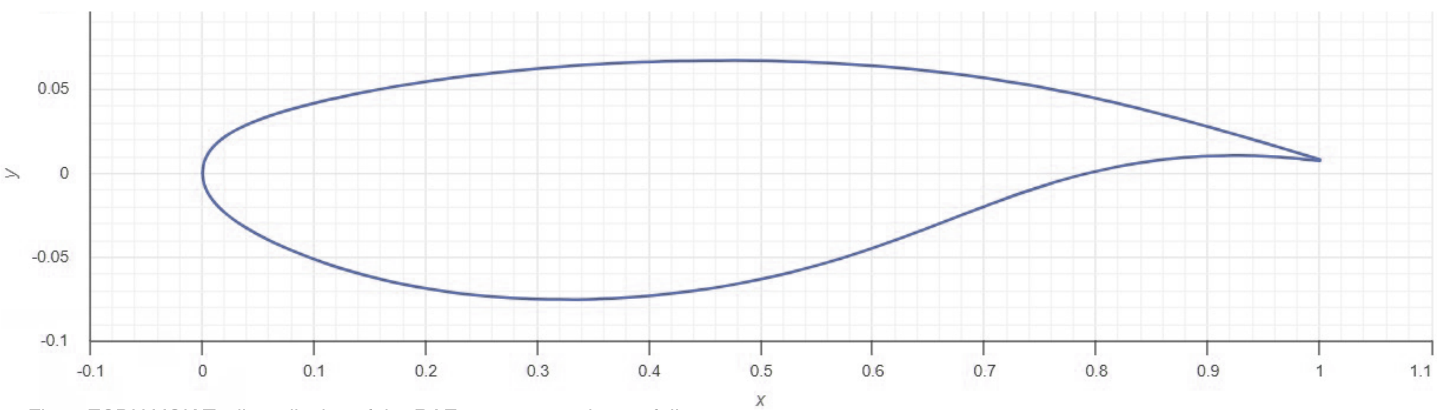

Fig. 7 ESDU VGK Toolbox display of the RAE 5225 transonic aerofoil

To set up a calculation, the Reynolds number and transition locations on the upper and lower surfaces are entered. Mach numbers and their corresponding angles of incidence are then entered into the "Cases Table", illustrated in Figure 8. Only one case is displayed initially but users can easily add more blank cases, or clone and edit a previous one. Cases can also be easily deleted as needed. When the calculation is initiated, each case is executed sequentially. Running the five cases shown in Figure 8 takes a total of 16 seconds when performed remotely on the ESDU servers.

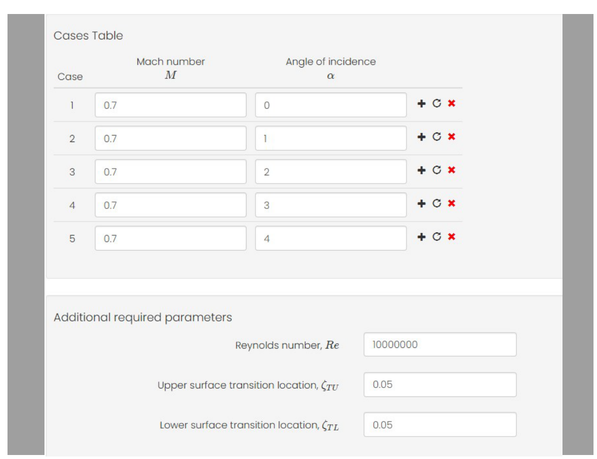

Fig. 8 Data entry using the ESDU VGK Toolbox "Cases Table"

All output can be viewed graphically and in tabular form. Examples are given in Figures 9 to 11. These graphs can be rescaled, zoomed in upon, and exported as tables in several formats.

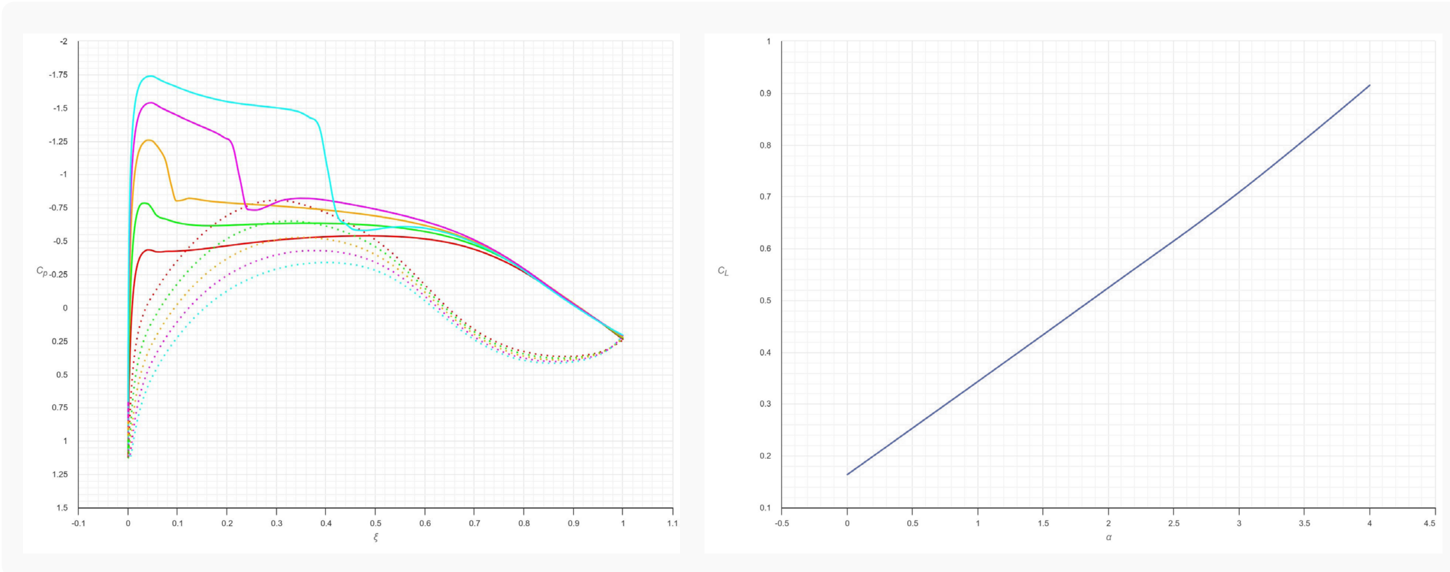

Fig. 9 Pressure distributions and lift curve of the RAE 5225 aerofoil at incidence angles of 0° to 4° and Mach No. = 0.7

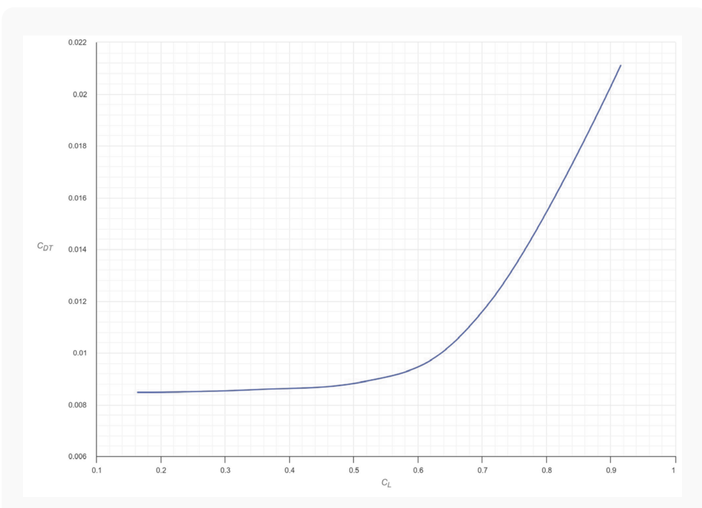

Fig. 10 Drag coefficient vs. lift coefficient of the RAE 5225 aerofoil at incidence angles of 0° to 4° and Mach No. = 0.7

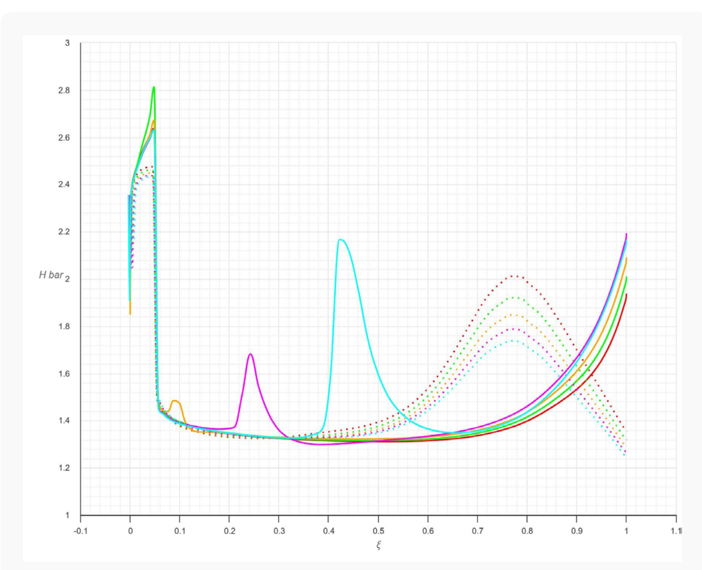

Fig. 11 Development of the boundary layer shape parameter on the RAE 5225 aerofoil at incidence angles 0° to 4° and Mach No. = 0.7

Error Trapping and Run Failures

Comprehensive error checking is implemented for data entry, accompanied by relevant warning messages. Programs like VGK, which model viscous effects using integral boundary layer methods, encounter limitations when significant flow separation occurs.

These programs can only predict aerofoil performance within a normal operating range. Consequently, a calculation failure may indicate that the incidence angles or Mach numbers being analysed are too high.

The ESDU VGK Toolbox captures calculation failures and displays a notification message. Additionally, boundary layer characteristics, such as the irregularities in the shape parameter shown in Figure 11, provide valuable insights into the limits of the useful operating range.

VGK's Impact on Aircraft Design and Performance

The new ESDU implementation of the VGK aerofoil method offers a compelling solution for addressing the challenges of modern aircraft design. By combining accuracy, efficiency, and user-friendliness, the ESDU VGK Toolbox empowers engineers to make informed decisions during the critical conceptual and preliminary design stages, ensuring:

Rapid and Accurate Predictions:	The VGK aerofoil method delivers swift and reliable predictions of aerodynamic performance, including lift, drag, pitching moment, and pressure distribution, across a wide range of flight conditions, from subsonic to transonic speeds.
Enhanced Design Insights:	The tool provides detailed information on boundary layer development, enabling engineers to assess flow separation risks and optimise aerofoil designs for maximum efficiency.
Efficient Workflow:	The intuitive GUI simplifies the setup process, minimising user effort and accelerating design iterations.
Scalable Computational Resources:	The ability to run entirely inside a modern web browser, on any platform, makes it accessible to a broad range of users, from seasoned aerodynamicists to students.
Versatile Output Options:	The tool offers flexible output formats, including numerical and graphical representations, facilitating data analysis and visualisation.

Incorporation of the ESDU VGK Toolbox into the aircraft design process can significantly streamline the development of new aircraft, leading to reduced costs, accelerated time-to-market, and improved overall performance.
By leveraging the power of the VGK aerofoil method, engineers can explore a broader range of design possibilities, identify optimal solutions, and ultimately contribute to developing more sustainable and efficient aircraft.

Expanding the ESDU VGK Toolbox

Future Developments

ESDU has developed specialised versions of the VGK aerofoil method. One of these versions is an inverse design procedure that generates the aerofoil profile based on a specified pressure distribution.

Additionally, ESDU offers the Viscous Full-Potential (VFP) method, a wing-body aerodynamic prediction code combined with an enhanced viscous method capable of handling minor flow separation.

Both codes are designed to run efficiently on modern computing hardware. ESDU plans to produce GUIs based on the ESDU VGK Toolbox model to enable similar functionalities.

ACCURIS

The ESDU VGK Toolbox

A Powerful Tool for Aircraft Design and Optimisation

Author: Dr D R Philpott