5. Overview of Configuration Aerodynamic Design:[*]

including the use of computational aerodynamics

5.1 Introduction

This chapter has several objectives. This is because configuration aerodynamics includes a broad range of activities. Having introduced a number of configuration concepts in Chapter 4, we now provide a brief discussion of the next aspects of configuration development. As aerodynamicists, we aspire to follow Küchemann,[1]

> ".. the main task that remains is to establish enough confidence to believe that, for the type of aircraft and mission under consideration, there exists regions of *no conflict* between the various essential characteristics, with which a set of design requirements can be met naturally. What we are really seeking is probably that "harmony" between elements,… So we are not out for "compromise" in the sense that we can achieve some desirable characteristic only by degrading another and where a "deal" is made at somebody else's expense. We shall endeavor to explain what is meant by this by giving examples of good design concepts…. On the other hand such "good design" is not likely to be one where the overall result is an "optimum" with regard to any single parameter at just one point. Instead, all the significant parameters are in harmony and not in conflict for a set of design points and off design conditions, and the final solution is sound and healthy. …It was Prandtl who introduced the concept of healthy flows, and we are well-advised to follow him and to search for sound and healthy engineering solutions when designing aircraft…"

Küchemann's words provide a high standard for us when we start an aerodynamic design. He was apparently the originator of the notion that controlled leading edge vortex flow could be used to obtain the required low speed lift for the Concorde. Without exploiting vortex lift for takeoff and landing, the Concorde concept would have been impractical. Thus his "healthy flows" include both attached flow and well-behaved separated flows. Here, we will approach aerodynamic design more modestly. For concepts such as the ones discussed in the previous chapter, first we need to define the aerodynamic design problem in terms of wing loading, W/S, and thrust to weight, T/W. This is a key part of the initial sizing activity, and is important in defining the cruise, and takeoff and landing lift coefficients. Next, we summarize the typical aerodynamic design tasks that occur during configuration design. This is followed by a discussion of the use of computational aerodynamics methods in design, and the computational aerodynamic design methodology that has emerged as key to achieving improved designs in practical design cycle times.

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[*] This is the first draft of this chapter, although it is compiled from several existing documents.

We continue to stress the importance of the underlying aerodynamic principles, and show how they contribute to configuration concept development. The details require further study on the part of the reader, and key references are provided. We also emphasize the geometry development associated with aerodynamic design, primarily using the exercises at the end of the chapter. Another objective is to illustrate the engineering aspects of the process. In terms of the use of computational aerodynamics, a key goal is to define a process for using software in aerodynamic design. Although the literature typically identifies a particular code as being used for the design, the reality is that the design is the result of work of the designer plus the code. Just having the code is not sufficient. I've heard this described as "just having a piano doesn't mean you are a concert pianist" or words to that effect.[*] Thus some skill is required to use the available methods, and we describe a process that helps the aerodynamicist evaluate when a code is giving the "right" answer—the infamous "sanity check" identified by Waaland as an important part of today's engineering using sophisticated codes.[2] Detailed examples of aerodynamic design are provided in Appendix D using the software available on the website, described in Appendix E.

5.2 Configuration sizing: Aerodynamic Considerations

Some of the key design characteristics can be defined with relatively little detailed information. An example is the wing loading, *W/S*. The problem is multidisciplinary, and wing weight is also important in selecting the wing size. However, we can define the problem reasonably well. The aerodynamic requirements are driven by two opposing conditions. To find the wing loading we first consider how the wing characteristics affect the value of the specific range, *sr*, of the airplane (typically given in units of nautical miles of range per pound of fuel used). An equation can be obtained (ignoring drag rise) that shows how the various design characteristics affect to the *sr*:[3]

$$sr_{\max} = \frac{1.07}{sfc}\left\{\frac{(W/S)}{\rho}\right\}^{1/2} \frac{\{AR\cdot E\}^{1/4}}{\left\{C_{D_0}\right\}^{3/4}}\frac{1}{W} \tag{5-1}$$

Here we see that a high value of *W/S*, high altitude flight (low density, ρ), high *AR* and *E* are desired. Similarly, specific range increases with low *sfc*, C_{D_0} and aircraft weight, *W*.

If we consider maneuvering flight, and takeoff and landing requirements, the demands on *W/S* are reversed. Consider the requirement for obtaining a sustained maneuver load factor:

$$n_{sustained} = \frac{q}{(W/S)}\sqrt{\pi ARE\left(\frac{1}{q}\left(\frac{T}{W}\right)\left(\frac{W}{S}\right) - C_{D_0}\right)} \tag{5-2}$$

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[*] by Mark Maughmer, of Penn State, describing airfoil design.

Clearly a low *W/S* is key a requirement for achieving a high value of $n_{sustained}$. Similarly, the takeoff distance is related to the so-called takeoff parameter, *TOP*, which also includes C_{Lmax}, is:

$$TOP = \frac{(W/S)}{C_{L_{\max}}(T/W)} \tag{5-3}$$

and the landing distance can be related to the approach speed:

$$V_{APP} = 17.15\sqrt{\frac{W/S}{\sigma \cdot C_{L_{APP}}}}, \qquad (knots) \tag{5-4}$$

In each of these cases a low *W/S* is desired (σ is the ratio of air density at a specific altitude to the density at seal level). In both cases, the need for a low *W/S* and high lift coefficient must be considered in a trade study.

So how is the selection of wing loading made? A constraint diagram is used to help the design team understand the requirements. Figure 5-1 from Loftin[4] illustrates the situation. Typical constraints for a transport aircraft are:

i) Cruise
ii) Takeoff field length
iii) Landing field length
iv) Second segment climb gradient
v) Missed approach
vi) Top of climb rate of climb

See Appendix C for the details of each of these requirements. They are defined very precisely by FAA and military specifications.

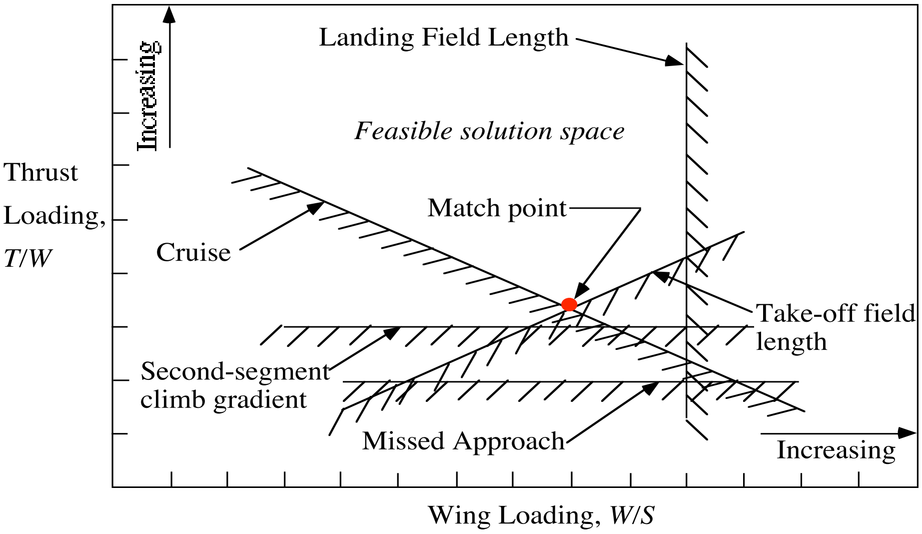

Figure 5-1. Conceptual illustration of a *T/W* – *W/S* constraint diagram (after Loftin)

For some cases involving point performance (local quantities) the trade between aerodynamics and structures can be found analytically. As an example, consider the transonic maneuver dominated fighter.[5] Minimizing the sum of the wing and engine weight, the maneuver lift coefficient can be found to be:

$$C_{L_{MDP_{opt}}} = \sqrt{\pi ARE\left(C_{D_{0_W}} + \frac{1}{q}\frac{dW_{WNG}/dS_W}{dW_{ENG}/dT_{REQ'D}} \right)} \tag{5-5}$$

We see the connection between the aerodynamic, structures and propulsion characteristics. See the reference (Ref. 5) for the derivation and example applications.

5.3 Overview of the specific aerodynamic design tasks

Initially, the aerodynamicist works with the design team to establish the appropriate concept(s) for the design requirements. The wing planform concept should be chosen, as well as the control concept, and the wing loading and thrust to weight, as described above. Targets are set for the design lift coefficients at key points in the mission, such as cruise, takeoff, landing, and any sustained and instantaneous maneuver requirements. The wing sweep and maximum *t/c* are naturally part of a design tradeoff between the structural and aerodynamic requirements. Another consideration may also be the wing volume available for fuel. Once the wing sweep and thickness distribution are selected, it will be very difficult to change them.

The baseline configuration geometry is obtained from the configuration designer. The aerodynamic design job starts with an analysis of the baseline geometry to establish the performance relative to the requirements. Then the aerodynamic designer modifies the geometry to improve the aerodynamic performance. Remember that one definition of aerodynamics is 50% flowfield, and 50% geometry (actually, geometry is much more than 50% of the day-to-day work of the aero designer). The aerodynamicist controls the flowfield by manipulating the geometry. Thus geometric modeling is a key aspect of an aerodynamicists' job. Appendix A provides the geometry definitions of commonly used airfoils and bodies of revolution.

The next item of business is to obtain the neutral point[*] of the configuration and work with the configuration designer to ensure that the wing is placed longitudinally on the fuselage to obtain the desired stability level. To do this you may need to do a minimum trimmed drag analysis to establish the desired stability level. The weights "guy" defines the center of gravity. If the airplane is to fly supersonically, the volumetric wave drag analysis should begin immediately, and the cross sectional area distribution should be developed to minimize the wave drag. An important aspect of this work is to ensure that the maximum cross sectional area is minimized.

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[*] Recall that the neutral point is the longitudinal location on the airplane where the center of gravity can be placed and the pitching moment will not change with angle of attack.

The other initial aerodynamic task is to estimate the parasite drag. This requires the wetted area of the configuration, given by component.

Once this work is done, the detailed aerodynamic design can begin. The nominal *t/c* distribution is typically defined during the initial studies, and once specified, an appropriate airfoil can be either picked or designed. Given the wing planform and thickness, the wing camber and twist are found. This is a major part of the detailed design effort. In addition, at this time the high lift system requirements are defined, and a high lift system design concept is selected to meet the requirements. Although the performance can be predicted with some certainty at key design conditions, the airplane handling qualities issues are associated with the boundaries of the flight envelope, where significant separated flow exists, as well as flight with unusual combinations of controls, engine thrust, etc. As such, once the basic aerodynamic design is done, much of the remaining effort, involving wind tunnel and flight testing, will be devoted to "fine tuning" the shape to obtain the desired handling qualities.

Another consideration in defining the aerodynamic shape is the difficulty of manufacturing complicated shapes. Ultimately, the master dimensions, or "lofting" group, controls the contour, and they may change the shape specified by the aerodynamicist. If the aerodynamicist specifies the shape at only a few span stations, *e.g.*, the root and tip airfoils and wing root incidence and wingtip washout, the contours between these control stations may not be the contours expected by the aerodynamicist (work the exercises at the end of this chapter to derive the details supporting this statement).

5.4 Use of computational aerodynamics in aerodynamic design

Today computational aerodynamics plays a key role in aerodynamic design, and we start with some sage words from one of the most inventive aerodynamicists in US history. We quote from R.T. Jones' book[6] before proceeding. Jones was concerned about the use of computational aerodynamics.

> "Aeronautical calculations today rely on the awesome power of the computer. However, as has been observed, power can corrupt. Equipped with an appropriate address book, giving the location and availability of various programs, the aeronautical engineer can now command the solution of a great variety of aerodynamics problems. Moreover, the capacity of the computer has made possible the inclusion of many small physical influences that until now had to be neglected but sometimes create a false impression of high accuracy. However, the basic physical assumptions of calculations, if they are discussed at all, are often not given adequate treatment. If 'computer aerodynamics' is to realize its full potential, then more attention must be devoted to these underlying principles."

Although the powerful software described by Jones can in many cases today be used on a laptop computer, the user must acquire experience with it before using it to make design decisions. In fact, experts are continually evaluating the accuracy of their methods. A series of test cases were developed by AGARD,[7] and a series of CFD Drag Prediction Workshops[8,9] have been held in the US to help them understand the accuracy of the methods. More recently, the use of CFD for stability and control characteristics prediction has attracted attention.[10] Below we list a few steps that should be taken when using computational aerodynamics programs.

5.4.1 Steps to take when using a program for the first time, and on a new configuration

The check list that we provide is perhaps obvious. In fact, it is sometimes apparently so trivial we are tempted to skip some of the steps. Speaking from personal experience, this is always a **bad** mistake.

Initial Validation

1. Demand that you be provided a sample input and output.

   It is impossible to use a code obtained from any source without checking that you have a version that actually works properly. Together with the user's manual, you must also obtain a sample input and corresponding output. Without these files, the code is unlikely to be worth your time to try and use.

2. Run the code yourself using the provided sample input.

   The next step is to run the code on the platform you intend to use with the input sample data set you were provided. Often the code won't run on a system even slightly different than the one on which it was developed. At this point, some interaction with the provider of the code is typically required. This should be done the same day you obtain the code![*]

3. *Carefully* study the output and compare with the sample output provided.

   You need to examine the input and the output obtained on your system with the sample output provided. There are two reasons for this. First, you need to make sure you get the same answers. Often you won't. When this happens you need to try to understand why the answers are different. Often, the sample input you were provided doesn't correspond exactly to the one used to create the sample output. I've been guilty of doing this. The second reason to study the sample input and output in detail is to learn the details of the code and it's capabilities. At this point, make sure you understand the nondimensionalizations, the detailed definition of the reference area, the exact coordinate system used, etc. Collect your questions and contact the person that sent you the code. However, don't call too quickly. Review your issues and make sure you really need to ask

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[*] Once I waited a few months before I tried to use a code I got from NASA because the code arrived too late to be used on the immediate problem it was requested for. When I did start to use the code, I found that the developer had passed away.

the question. You need to establish that you are a serious and informed user if you expect to get support. This is especially true if you are not paying for support.

4. Investigate sensitivity to various parameters.

   Today's aerodynamics codes come with numerous options. You will never be able to test every combination. However, establish which one's are key for your problem and investigate their effects. The options typically come in two classes. One class will be associated with obtaining the numerical solution. This includes convergence criteria, numerical step sizes, etc. This also includes the number of panels, the number of grid points, etc. Make sure you understand how to exercise the code to obtain a solution that is converged with respect to these factors. Often, to suggest the code is fast, these factors will not be set at default values that result in a converged solution. The other class of options are associated with the flow physics. They include the options for turbulence models, boundary condition treatment, and possibly differences in behavior depending on Mach and Reynolds numbers. This type of study is another important step in developing experience using a particular code.

Configuration Buildup Approach

Once you have performed the steps outlined above, you are ready to start using the code for your own work. To do this,

1. Make up your own test case.

   Pick a case "close" to the one you are trying to solve and for which there is an analytic solution available, a published numerical solution or experimental data. Run the code to compare to the other results. See how closely you match this result, and try to understand the reason for any differences.

2. Finally start to use the code for the configuration you are interested in investigating.

   - Start with the simplest possible model. This is probably an isolated airfoil or wing. Investigate the solution and its convergence process. Study the physics.

   - Add the tail and/or canard to the isolated wing case. Does the code still work? What is the effect of the added component?

   - Add the fuselage to the isolated wing case. What are the fuselage effects on the results?

   - Finally, run configuration with the full level of geometric complexity. Following this procedure you will gain confidence in the results, and be able to identify the contributions of the components to the complete results.

5.5 A Review of detailed computational aerodynamic design approaches

This section originated in a report written nearly thirty years ago.[11] Revisions have been made to reflect current practice. Surveys of the use of computational aerodynamics have appeared regularly since computational aerodynamics began to be used extensively in aerodynamic design. Among the many reviews, we cite two relatively recent surveys. Jameson[12] provides a survey of CFD, and Johnson, Tinoco and Yu[13] provide specific examples of Boeing – Seattle use of CFD applied to their designs.

5.5.1. Introduction: analysis vs design

Although the use of the computer to simulate the flowfield about a vehicle with a specific geometric configuration is an extremely useful and important capability, it is an indirect response to the aerodynamic design question. The aerodynamic design question is typically posed at several levels, starting with some vague and general question about the "best" shape of the airplane for a particular mission, and proceeds to more specific and detailed questions concerning the actual wing (and fuselage) lines, subject to a large variety of constraints. In the "old paradigm" the aerodynamicist designs a wing using the methods of computational aerodynamics, the lines are given to the contour development group, and a wind tunnel model is built and tested. In the analysis mode, the aerodynamic computer programs are being used to simulate a wind tunnel. Of course, the computer simulation can be used much sooner in the design cycle than a wind tunnel test and this strategy should produce an improved final design at a reduced cost, in a shorter time period. This was the proper initial introduction of computer simulations into the wing design process. Indeed, this technique was used for subsonic and supersonic wing design since the 1960s employing linear aerodynamics methods. Subsequently, transonic wing design using fully transonic three-dimensional wing-body computer methods was done in a similar manner.

Once the computer is introduced into the design cycle, it becomes evident that it can be used in a fundamentally different mode than to simply supplement wind tunnel testing. The use of flowfield simulation in this manner is naturally referred to as the "design mode," as opposed to the "analysis mode" of operation. A "design mode" has been available for linearized subsonic and supersonic flowfields since shortly after the analysis codes became available. The most extensive use of a "design mode" appears to have been the elaborate system of linear aerodynamics supersonic wing design codes that evolved from the work of Carlson and Middleton[14] developed for the US SST program. After a brief review of the design problem and some of the methods used over the years, we describe the current approach to aerodynamic design. We include a few illustrations of very simple problems to provide some insight. Specific codes will be discussed in more detail in subsequent chapters.

5.5.2. Review of the Computational Design Process

A variety of possibilities emerge when the problem formulation for a "design mode" of operation is explored. The reason for this range of possibilities can be attributed to the manner in which the design problem is posed, as noted above. Ideally, the aircraft designer would specify the aircraft mission (or missions) and a computer program would provide the detailed lines of the optimum aircraft. Such a smart computer program will not exist for some time. However, most aircraft companies and governmental agencies routinely employ programs that predict the gross features of an "optimum" aircraft for a particular mission with some assumption regarding the rate of development of various technologies. These programs use low fidelity models of the various disciplines, as well as databases developed from previous aircraft designs. Typical aerodynamic outputs from the programs are takeoff gross weight, wing area, wing loading, and planform details such as *i*) aspect ratio, AR; *ii*) taper ratio, λ; *iii*) sweepback, Λ; and *iv*) thickness ratio, t/c. Usually a target/assumed drag level for the configuration is also specified. Examples of this type of program are the NASA ACSYNT[15] program, and the NASA program FLOPS.[16]

Hence, the computer is used to determine the overall features of the required airplane. The typical aerodynamic design problem thus becomes less vague and more manageable, with the statement being reduced to something along the following line:

Given: • AR, λ, Λ, t/c (basic geometric requirement)

• M_∞, Re (flight regime)

$$\left.\begin{array}{l} \bullet\ C_{L_{cruise}} \\ \quad or \\ C_{D_{max\ allowable}} \end{array}\right\} Design\ Goal$$

Find :

$$\left.\begin{array}{l} \bullet\ C_{D_{\min}} \text{ for } C_{L_{cruise}} \\ \quad or \\ C_{L_{\max}} \text{ for } C_{D_{max\ allowable}} \end{array}\right\} Design\ Goal$$

• Detailed Geometry. Detailed Aerodynamic Aircraft Design Definition, subject to geometric constraints on twist, camber, root bending moment, etc., and aerodynamic requirements on performance at other flight conditions.

At this point we could begin to consider the use of a computer code directly to help determine the optimum aerodynamic shape and performance that can be obtained for the specified problem. More typically, the aerodynamic designer employs his experience and judgment to specify a desired pressure distribution (unfortunately, it appears that designers with this ability are becoming rare in 2006). This type of program is usually described as an "inverse method," while a program that attempts to address the problem more immediately is usually termed an "optimization method." The "classical optimization" approach uses well-established numerical optimization methods to find the aerodynamic shape. Each of these approaches has its own strengths and weaknesses. A contrast between optimization and inverse methods can be summarized as follows:

"Classical" Optimization	**Inverse**
• Requires many analysis submissions for a single design case.	• Generally almost as fast as a single analysis
• Solution depends critically on the user assumed form of the answer	• The geometry may not always exist for a given pressure distribution.
• Can handle a variety of geometric and off design constraints	• Difficult to treat off design and geometric constraints.
• If performed through a large optimization code, solution is not obtained from "aerodynamic thinking."	• Solution is a direct result of best current "aerodynamic thinking."

Another drawback of the optimization approach is that the path taken to the final result is often rather obscure and the relative importance of the various aspects of the final design produced in this manner are not readily apparent.

The original numerical optimization techniques employed in the design methods were of the "search" type, and did not employ any of the elements of calculus of variations to obtain the maxima. More importantly, in fluid mechanics it was not clear how to find the aerodynamic gradients of design variables without using simple finite difference approaches. This meant that many additional calculations had to be made at each optimization iteration. Although an entire book[17] had been devoted to aerodynamic optimization using calculus of variations, these concepts were not used until Antony Jameson introduced the current modern methods for aerodynamic design. His adjoint methods are closely connected to classical calculus of variations and control theory.[18] The advantage of current modern methods is that the gradients of the solutions can be obtained very efficiently.

5.5.3. Examples of Design Methods and Issues Drawn from Two Dimensions

A variety of numerical approaches have been used to design transonic airfoils. The book edited by Thwaites[19] discusses the classical approaches to the incompressible inverse methods and points out that some judgment must be used by the designer in specifying the desired pressure distribution; a solution does not necessarily exist. You cannot specify any arbitrary pressure distribution and obtain a real geometry. Inverse methods for transonic speed airfoil design have to contend with this same problem. However, in practice the aerodynamicist has been able to use inverse methods without any undue hardship. A current review of inverse methods is available in the AIAA book edited by Henne,[20] in articles by Drela[21] and for transonic flow byVolpe.[22] The programs have proven to be very useful.

Another approach to transonic airfoil design must be mentioned in any review, although it isn't used today. Hodograph methods were used to design some very good airfoil sections. The method worked well in the hands of the skilled users at the Courant Institute.[23] One of the main problems with the method was the problem of extending it to three dimensions.

The numerical optimization approach to airfoil design is more recent, unlike the inverse methods, which were available in the 1940s for subsonic flows (like many of the currently used aerodynamics methods, inverse methods for detailed aircraft work were not routine engineering tools until the widespread availability of computers). An initial study of numerical optimization applied to aerodynamic design was presented in 1974 by Hicks, Murman and Vanderplaats.[24] The underlying idea in this approach was to couple a modern numerical optimization code with an aerodynamic analysis code. The airfoil design problem is then cast as an optimization problem and the entire apparatus associated with optimization methods is brought to bear on the problem. The most attractive aspect of the optimization method is its ability to handle design constraints. These constraints include both off design performance requirements and design point geometry restrictions. The report by Vanderplaats and Hicks[25] provided a detailed description of the techniques used to formulate the design problem as an optimization problem.

The optimization method of aerodynamic design has become the standard approach to aerodynamic computational design. However, there are some drawbacks that need to be addressed. These drawbacks are in part related to computer run times. In optimization methods jargon, optimization methods minimize an "objective function," which is a function of a set of "design variables" subject to a set of "constraints." The "objective function" could be drag, for example, while the "design variables" are typically the variables used to specify the shape of the airfoil. The constraints could be a minimum lift coefficient, a prescribed pitching moment, airfoil thickness, off-design drag values, or virtually any other requirement that might arise in practice. The selection of the appropriate *objective function* and *design variables* is crucial to the success of optimization methods.

The *design variable* specification is perhaps the biggest challenge in the application of optimization methods. In principle, the number of airfoil ordinates used to specify the shape could each be used as design variables, however, if 60 upper surface and 40 lower surface points (a typical number of ordinates) are used, then there are 100 design variables. In practice, no more than about 10 independent design variables can be treated reliably. Thus, the airfoil shape must constructed from *shape functions* that describe more than a single ordinate; *i.e.*, coefficients of polynomials used to approximate airfoil shapes. Experience led to the realization that polynomials were not appropriate shape functions, and schemes that use linear combinations of present supercritical shapes and local geometric perturbations to these shapes appear to be the most practical method to obtain useful results with a small number of design variables. Thus the linear combination of known airfoil shapes, as used by Vanderplaats and Hicks,[25] and the use of shape functions obtained using inverse methods proved very effective.[26] This approach also proved effective in three dimensions, although using a slightly different approach. It is important to realize that the optimization method will only identify the best of a particular set of possible airfoil shapes arising from the shape functions. If the actual optimum airfoil is not among this set of shapes, the method cannot find this shape. Hence, the optimization methods also require the user to apply insight into the problem.

The current state of the art consists of work addressing three key areas. Jameson and co-workers have addressed the issue of low-cost gradient calculations.[27] They combined the efficient calculation of gradients with a numerical optimization procedure to obtain an aerodynamic design procedure. Their work has been demonstrated in numerous applications.[28] The other problem is the need to avoid designs that are too narrowly optimized. Any practical design must be efficient over a range of flight conditions, and in the presence of possible uncertainty in the shape specification. The work of Huyse and co-workers[29.30,31]provides practical methods of addressing these issues. The third key area is the work at Virginia Tech[32] addressing the issue using of high-fidelity aerodynamics in the early stages of design by exploiting parallel computing to pre-compute aerodynamic results for the design space of interest and using statistical methods to interpolate this “data base” during optimization studies. This approach is tailored to multidisciplinary design where other disciplines are also involved in optimizing an entire system.

The comments concerning inverse and optimization methods in 2-D in the previous section carry over to the 3-D design case. One curious aspect of the 3-D inverse and optimization methods is that the solution may be non-unique near the wing root, a result that was reported by Sloof[33]. This occurs because the same pressure distribution can be obtained by shaping the surface on either side of the junction. Although complicating the design method, the result is more freedom available to the designer.

In the next section, we illustrate the possible use of the three-dimensional transonic methodology in a design environment by application to two model problems.

5.5.4. Application of the 3-D Transonic Program to Wing Design Problems

The feasibility of using the present computer program in transonic wing design as more than a straightforward analysis tool was investigated through two model problems. The first model problem was conducted making use of the NASA optimization program CONMIN. The main purpose of the exercise was to gain familiarity with the use of optimization codes in aerodynamic applications. The second model problem was undertaken in order to assess the effort required to introduce an automatic geometry alteration loop driven by the results of a previous iteration into the code. The stability of this type of iterative procedure is also of interest.

The first model problem provided an opportunity to obtain experience using CONMIN. The problem was specified simply as follows: Using lifting line theory for the aerodynamic representation of the finite wing, have CONMIN determine the twist distribution required to minimize the induced drag. In this case the exact solution can be found to be

$$\alpha_g(\eta) = \frac{C_L}{\pi AR}\left\{1 + \frac{AR(1+\lambda)}{\pi}\cdot\frac{\left(1-\eta^2\right)^{1/2}}{\left[1-(1-\lambda)\eta\right]}\right\} \tag{5-6}$$

for straight tapered wings. For an untapered wing, Eqn. (5-6) for α_g shows that the basic incidence variation along the span is elliptic. Observing the functional form of the exact solution, we note that this particular ratio of the root of a second order polynomial to a first order polynomial would have been an unlikely selection for the assumed variation of spanwise twist. To repeat, unless Eqn (5-6) was contained as a subset of the functional forms selected for the optimization study, the true optimum twist distribution would not have been found. This fact serves to demonstrate the importance of using the insight gained from analytical theories to maximize the benefits of numerical solutions. Indeed, initial efforts to obtain the minimum solution using a cubic polynomial for the span variation of twist were not particularly satisfying. The results never approached the true minimum, and apparently there were several combinations of coefficient values that were equally close to true minimum, such that several substantially different answers for the twist variation could be obtained, depending on the initial guess supplied to the program. These calculations typically took on the order of ten iterations, each of which required a number of function evaluations to obtain the local gradient of the objective function. In aerodynamic terms this means that there were ten main executions of the aerodynamic program, and a number of "small" executions which were required to be run long enough to provide the local gradient of the solution with respect to each design variable. It is clear that this can quickly lead to an immense amount of computational effort.

Finally, the optimization scheme was run with the design variables consisting of a coefficient to Eqn. (5-6) and the coefficient of an additional term added to Eqn. (5-6). Figure 5-2 shows the path through design space for this two parameter optimization run. Note that the minimum occurs when $\beta_2 = 0$, and $\beta_1 \approx 1$ ($\beta_1 \neq 1$ exactly because a lift curve slope slightly different than 2π was employed). The run terminated after eight iterations, with the numerical solution predicting that the optimum had been achieved. Figure 5-3 shows a close-up view of the last iterations of the path through the design space. The result demonstrated that the program could in fact select the true optimum if it was embedded in the design variable space. This effort demonstrated both the difficulties and possibilities associated with the use of optimization methods.

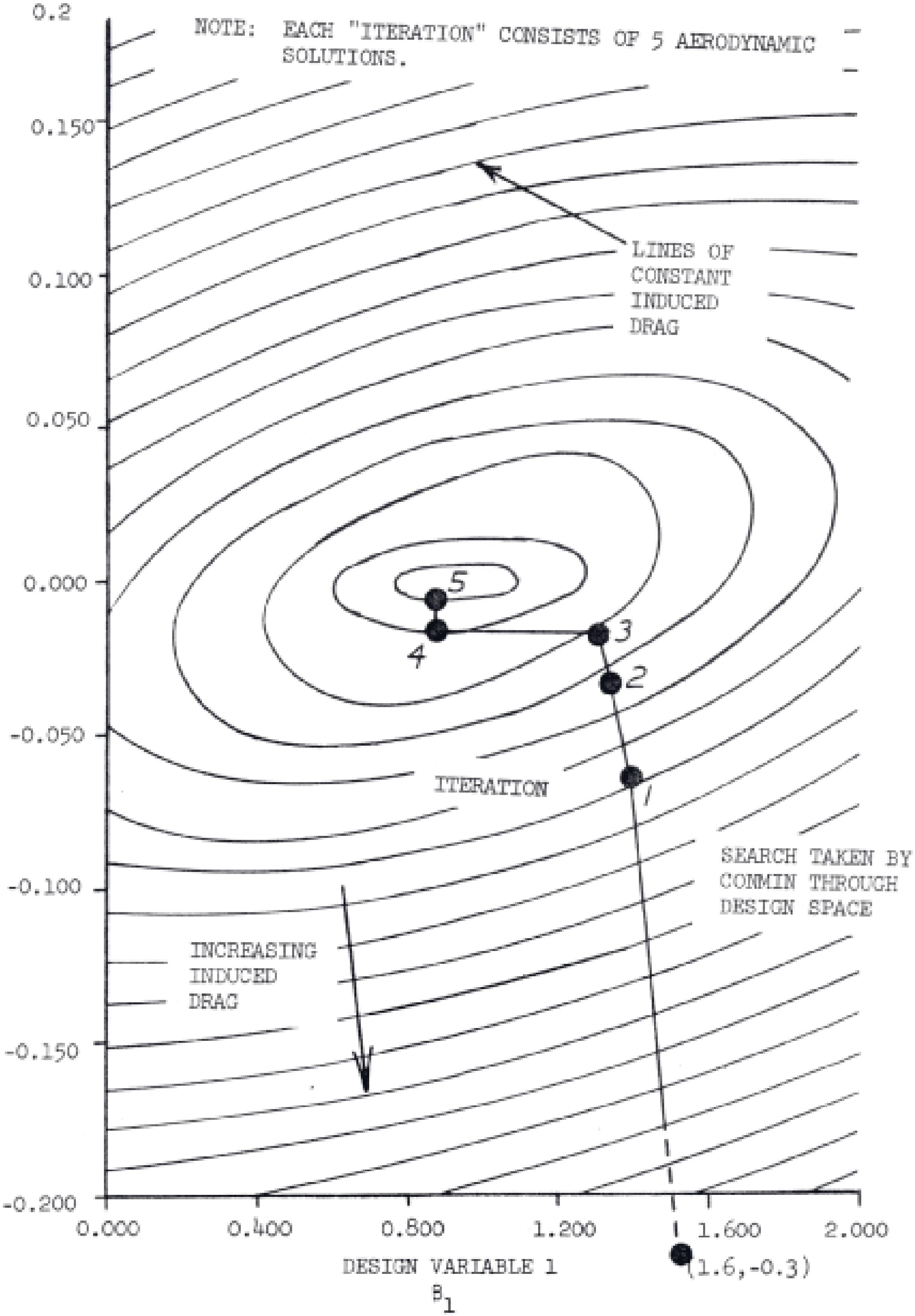

Figure 5-2. Twist Optimization Using numerical optimization and Lifting Line Theory.[11]

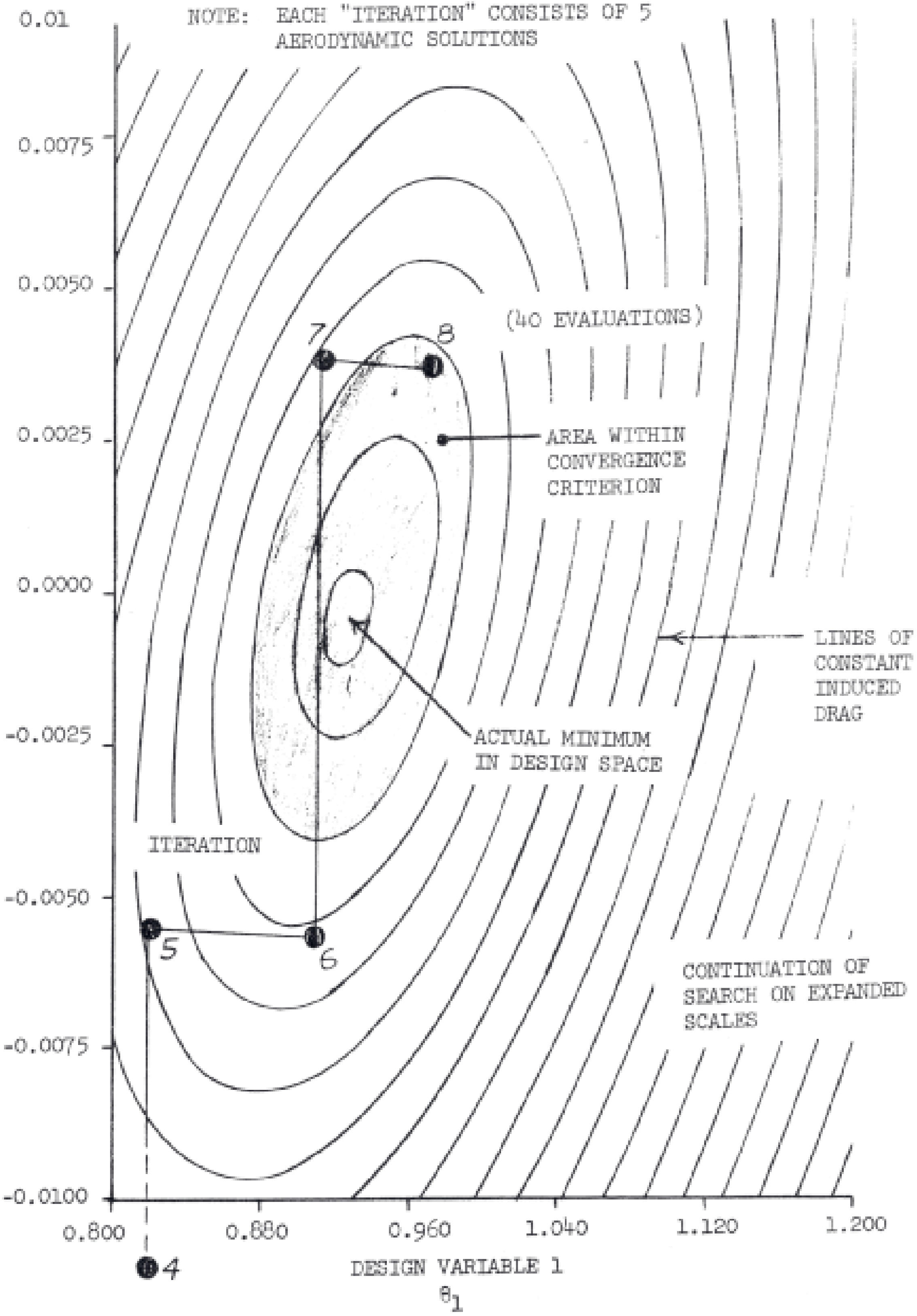

Figure 5-3. “Close Up” of the final iterations through the design space.[11]

The second model problem is considerably different in concept. For this problem the question posed was simply: For a given planform and spanload, determine the twist required to produce the spanload. Initially lifting line theory was employed to verify that the basic iteration scheme adopted would converge for a simple aerodynamics model before attempting to incorporate the iteration into a transonic computational method. The twist was determined by adjusting the section incidence at the finite set of span stations at which the computation provided results, without making any assumption concerning the functional relationship between the incidence at adjacent span stations. The basic iteration tested was

$$\alpha_{D_j} = \alpha_j^K + \left(\frac{C_{l_{D_j}} - C_{l_j^K}}{C_{l_{\alpha_j}}} \right) \tag{5-7}$$

where j denotes the particular span station, D denotes the design condition and K indicates the iteration number, and $C_{l\,\alpha}$ is approximated by

$$C_{l\alpha}^{\,k} = \frac{C_l^k - C_l^{k-1}}{\alpha^k - \alpha^{k-1}} \tag{5-8}$$

For the lifting line simulation this iteration procedure converged to the exact solution given by Eqn. (5-6) in about four or five iterations. This result was obtained without difficulty even though the approximation given in Equation (5-8) is poor for numerical computation due to the progressively smaller differences between the values as the iteration converges.

Equation (5-7) is equivalent to a more general form:

$$\{\alpha_D\} = \{\alpha^K\} + \left[\tilde{A}^{K-1}\right]^{-1} \{C_{l_D} - C_l^K\} \tag{5-9}$$

Where $\left[\tilde{A}\right]$ is an approximation to the actual influence coefficient matrix which relates C_l and α:

$$\{C_l\} = [A]\{\alpha\} \tag{5-10}$$

In the present method $\left[\tilde{A}\right]$ has been given by the extremely simplified relationship in Eqn (5-8) for the diagonal terms, with the off-diagonal terms assumed to be zero. This result shows that $\left[\tilde{A}\right]$ can be crudely approximated if an iteration is used to determine the final result is allowed. Naturally, as the approximation to $\left[\tilde{A}\right]$ improves, the number of iterations required is reduced.

Modifications to the basic inviscid program to include this type of iteration scheme were incorporated without difficulty. It was found that a relatively fine grid was required to obtain the straight wing result computed previously using the lifting line aerodynamic mode. Refinements to the iteration included the use of underrelaxation of the twist increment and the use of the initial C_{l_α} value for all iterations. These refinements led to a smoothly converging solution that took about fifty percent longer than the basic solution. The method was then applied to a 45° swept untapered wing. The refined procedure led to a solution with the results obtained shown in Figure 5-4, which also contains the straight wing results. In this case, attempts to compute the result while C_{l_α} changed from iteration to iteration led to a diverging result at the point where no shift in angle was required (about 45% semispan), and shows that in an actual production program an improved approximation to **A** should be used. However, this improved **A** can be constructed without difficulty so that a design option of the type described above could be included in the basic analysis program without difficulty.

In this section we have demonstrated the variety of possibilities that arise when incorporation of design options is suggested. One of the options would provide immediate benefits to the designer, allowing analysis codes to be easily modified to provide design options.

5.5.5 Design within the contest of Multidisciplinary Design Optimization

Broader issues related to aerodynamic design within the MDO context, which considers other disciplines simultaneously have been the subject of research in the 90s at Virginia Tech. An overview of our thinking is given in Giunta, *et al*[34]. The ability to combine high fidelity results from numerous disciplines in early design is the area of research of importance for configuration aerodynamics.

5.6 Summary of the status of aerodynamic design

Aerodynamic optimization has become practical using CFD. The ability to use it in conjuncture with other disciplines simultaneously is currently being addressed. We conclude with a quote from a recent paper by Jameson:[27]

> "The accumulated experience in the last decade suggests that most existing aircraft which cruise at transonic speeds are amenable to a drag reduction of the order of 3 to 5 percent, or an increase in the drag rise Mach number of at least 0.02. These improvements can be achieved by very small shape modifications, which are too subtle to allow their determination by trial and error methods. When larger scale modifications such as planform variations or new wing sections are allowed, larger gains in the range of 5-10 percent are attainable."

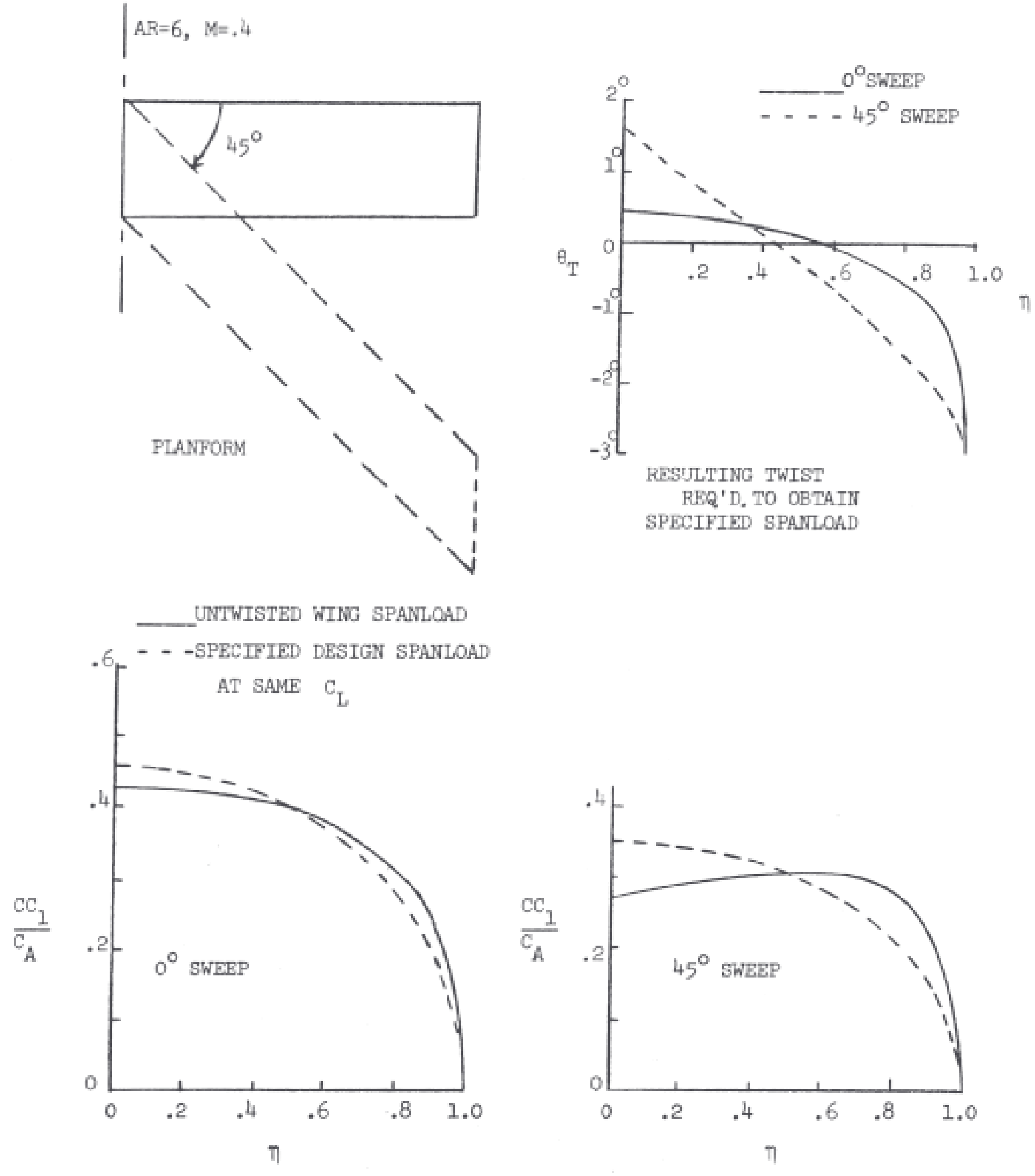

Figure 5-4. Wing twist design results using simple modifications to an analysis code.[11]

5.7 Exercises

1. Estimate W/S for a variety of aircraft types. What conclusions can you make?
2. Estimate cruise C_L for a variety of aircraft types. What conclusions can you make?
3. Straight line wrap: t/c – considering a simple trapezoidal planform, derive an expression for the maximum thickness distribution between the root and tip stations when different maximum t/c's are specified at the root and tip station. Illustrate your result by plotting the

maximum thickness to chord distribution across the span for an aspect ratio 7, taper ratio 0.3 wing. The root *t/c* is 12% and the tip *t/c* is 6%.

4. Straight line wrap: twist - considering a simple trapezoidal planform, derive an expression for the twist distribution between the root and tip stations given the root and tip twist. Illustrate your result by plotting the spanwise twist distribution between the root and tip for an aspect ratio 4 wing with a taper ratio of 0.2. The root twist is +2° and the tip twist is –4°.
5. Derive the formula for the twist distribution required to achieve an elliptic spanload distribution using lifting line theory (hint: use the monoplane equation). For the wing in exercise 5., plot the required spanwise twist distribution required for a lift coefficient of one. Compare your results with the results from 5.
6. Use **LamDes** to obtain the required twist distribution for the wing in 5, assuming the wing has a leading edge sweep of 45°.

5.8 References

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