1.0 Introduction

1.1 Motivation

Engineering systems of practical interest are usually characterized by complex interactions occurring between various disciplines. In some cases, simplifying assumptions may be made, with reasonable accuracy, that decouple these disciplines. In other situations, the interactions themselves may produce changes in the system's response that is of the same order of magnitude as the decoupled analyses. For example, in a system such as an aircraft wing, aerodynamics, structures, and controls all contribute integrally to its behavior and performance. If, for example, the structures discipline is neglected in the analysis of a wing in transonic flow, where large elastic deformations are present, predicted rigid-wing lift calculations have been found to be in error by more than 25% in some cases. Similar scenarios may be postulated for the controls discipline for the suppression of aeroelastic instabilities such as wing divergence and flutter. This reality, therefore, forces the design engineer to consider multiple disciplines in order to accurately evaluate the sensitivities of system performance.

Sensitivities of system performance, commonly referred to as sensitivity derivatives (which provide a measure of *how* the system output will respond to a change in system input), are an invaluable commodity to the designer and may be used to make informed decisions about possible directions for improving existing designs. When these derivatives are used in conjunction with a numerical optimization technique, procedures may be developed that are not biased by intuition or experience (or lack thereof) [1]. Hence, the motivation for performing accurate multidisciplinary analysis and sensitivity analysis becomes obvious.

1.2 Survey of Recent Advancements

Multidisciplinary analysis and optimization (MDA&O) by its very name implies a coming together of various disciplines, each one having a distinct historical development, and any attempt at a comprehensive review of such a vast subject matter would require numerous volumes. As a visualization tool, one possible interpretation of an MDA&O procedure is outlined in Fig. 1.1 for the coupling of the fluid and structures disciplines. This outline will serve as a road map to guide the discussion to follow and later as a flowchart for the research conducted in the present work. The survey presented in the subsequent sections include some of the most recent advancements in the respective topic areas, and the interested reader may use this as a starting point for further study. In each case, however, sources of more complete reviews are cited.

1.2.1 Aerodynamic Design Optimization

In the mid-70s, researchers [2-6] began exploring the use of numerical optimization techniques for the design of aircraft components. These early studies primarily focused on airfoil and wing design using low fidelity fluid models for the analyses and finite-difference calculations for gradient information. The inability of these fluid models to accurately predict nonlinear phenomena limited their applicability. By the mid-80s, computational resources were available that permitted aerodynamic simulations using the higher fidelity Euler and Navier-Stokes equations about isolated components and moderately complex configurations. Then Sobieski [7] challenged the aerodynamic community to extend their computational fluid dynamic (CFD) algorithms to include the shape sensitivity analysis of the geometry. This plea ignited intense studies aimed at developing methods that would render the use of nonlinear aerodynamics in shape optimization feasible.

With improvements in computer speed and memory, as well as advances in computer architectures, numerous aerodynamic design optimization procedures [8-25] have emerged which directly couple the fields of computational fluid dynamics (CFD), sensitivity analysis, and numerical optimization. These procedures, schematically shown in Fig. 1.2, have enormous potential as design tools and are therefore receiving considerable attention in the aerospace, automotive, and biomedical research communities (among others). Moreover, bottlenecks associated with the in-core memory needed for the analytic evaluation of discrete sensitivity derivatives, appear to have been addressed [13] via the use of an incremental iterative solution of the sensitivity equation [15] where memory efficient methods [26] are used to construct Jacobian matrix-vector products.

The other limiting factor governing the acceptance of these shape optimization procedures is the large CPU times incurred when nonlinear fluid models are considered. Reductions of the excessive CPU run times required to perform the design optimization are being explored through the use of simultaneous analysis and design optimization (SAADO) [27-29], *one-shot* methods [21], pseudo-time methods [30], and parallel computing architectures [24,31]. Another crucial capability which these aerodynamic optimization procedures must have to become useful design tools is the ability to analyze and design complex configurations of practical interest. Elliot and Peraire [32], with regards to the geometrically complex domains associated with the integration of the engine into the wing design process and to the possible multipoint design of the aircraft's high lift system and cruise design, assert that this capability may provide *"the step that determines the economic viability of the vehicle"*.

As recently noted by Reuther et al. [33] "*while flow analysis has matured to the extent that Navier-Stokes calculations are routinely carried out over very complex configurations,* *direct CFD based design is only just beginning to be used in the treatment of moderately complex three-dimensional configurations"*. This shortcoming is primarily due to the fact that to generate a single structured grid about such a configuration is difficult, if not impossible. Thus, to handle a typical complex geometry of practical interest, some sort of domain-decomposition scheme must be incorporated into the design code. For structured grid solvers, these techniques include multiblocked [34,35], zonally patched [36,37], and overlapped [38,39] (sometimes referred to as Chimera [40]) grid algorithms. However, as the geometric flexibility of the method increases, so does the complexity of the underlying algorithm. Since the use of sensitivity analysis to evaluate the needed gradients for a numerical optimizer is still evolving, little work has been done toward extending these algorithms to include these domain-decomposition methods. The research which has been accomplished has mostly concentrated on the use of multiblocked grids. To this end, Reuther et al. [33] have developed a multiblock-multigrid adjoint solver via a "continuous" or "control theory" approach [41,42] (see sections 2.2 and 3.3 for a description of the continuous and discrete approaches) which was applied to the wing redesign of a transonic business jet. Eleshaky and Baysal [43] developed a multiblock "discrete" adjoint solver which was applied to a simple axisymmetric nozzle near a flat plat. As for the use of the more advanced domain decomposition methods (zonal and overlapped grids), and combinations of the three various types, Taylor [44,45] has differentiated an advanced flow-analysis code to perform the discrete sensitivity analysis.

Unstructured grid schemes provide an alternative to resorting to structured-grid domain-decomposition methods to cope with complex configurations. Since triangles and tetrahedra are the simplest geometric shapes possessing area and volume, respectively, they are capable of resolving irregularly shaped domains easier and with greater efficiency. Another attribute of unstructured grids is that they may be adapted and locally enriched where needed without affecting other regions of the mesh. Examples of mesh refinement techniques for aerodynamic simulations may be found in references 46 and 47.

As for unstructured grid approaches to aerodynamic design optimization, Beux and Dervieux [48] did perform spatially first-order accurate sensitivity analysis and optimization of a two-dimensional nozzle using a continuous adjoint method to derive the optimality conditions, but reverted to a discrete approach for computer implementation. Orozco and Ghattas [23] proposed an infeasible path method similar in nature to a SAADO approach where a Galerkin finite-element discretization of the nonlinear potential flow equations was performed. In Ref. 23, target-pressure distributions were matched on a subsonic airfoil using what was referred to as the coordinate basis infeasible path (CBIP) method. Newman, Taylor, and Burgreen [49] developed a two-dimensional, and later a three-dimensional [13], second-order spatially accurate discrete sensitivity analysis approach which has been used to perform the design optimization of airfoils and transport wings in transonic flow. More recently, Newman, Taylor, and Barnwell [50] have performed the shape sensitivity analysis and design optimization of a subsonic, high angle-of-attack multielement airfoil and of a full Boeing 747-200 aircraft. Elliot and Peraire [32] have also developed an unstructured discrete-adjoint sensitivity analysis approach which was used to match target pressure distributions for a two-element airfoil, a 3D infinite wing, and a wing-body configuration. Subsequently, Elliot and Peraire [14] have applied their algorithm to perform the inverse pressure design of a business jet wing immersed in transonic flow. An equally impressive use of unstructured grid approaches for the design of geometrically complex devices has been performed by Burgreen and Antaki [51]. In Ref. 51, CFD-based design optimization methods are used to improve the thrombogenic performance of an axial flow blood pump. The research of Burgreen and Antaki [51], furthermore, represents the expansion of traditional aerodynamic design optimization procedures into the biomedical field to aid in artificial heart design. Anderson and

Venkatakrishnan [52] have recently developed an unstructured grid approach to sensitivity analysis which actually utilizes a continuous adjoint approach for computer implementation for the first time. Moreover, in Ref. 52, limitations of the continuous adjoint approach are discussed and a hybrid continuous-discrete approach, which addresses some of these deficiencies, is developed.

A detailed and concise review on the use of sensitivity analysis in aerodynamic shape optimization has been previously reported by Taylor et al. [53]; the reader is strongly urged to seek this source for research performed prior to that listed above.

1.2.2 Static Aeroelastic Analysis

Again, with the furtherance of modern computers, numerical simulations are being used more frequently to aid in the design process. To be useful, these simulations must predict quantitatively the features of the actual model under consideration in both an economical and reliable manner. An aircraft in flight, for example, is subjected to complex interactions between aerodynamics, structures, controls, and the propulsion system. Traditionally, these disciplines were uncoupled and solved separately in the absence of powerful computational resources [54]. This approach, although less expensive, may neglect the nonlinearity associated with the interaction and, thus, only provide limited information. Most modern commercial and military aircraft operate in the transonic flow regime, where flow nonlinearities such as shock waves and large structural deformations may be present. Numerous computer codes from both the research and commercial communities have been developed to account for these interactions. Some familiar examples of commercially available software that can, among other capabilities, solve the integrated aerodynamic and structural analysis include NASTRAN [55], ELFINI [56], and ASTROS [57]. However, these codes utilize linear aerodynamic methods, which limit their applicability. More advanced aeroelastic codes, which take advantage of modern CFD techniques, include

XTRANS [58], CAP-TSD [59], and ENSAERO [60]. The higher fidelity Euler and Navier-Stokes equations are incorporated in ENSAERO, whereas the other codes rely on transonic small-perturbation theory. A recent concise review of aeroelastic codes and capabilities has been given by Edwards and Malone [61] and by Batina et al. [62]; the reader is referred to these sources for further discussion.

The mathematical modeling of the individual-discipline state equations, interdisciplinary interactions, and configuration geometry is governed by a balance between the requirements of the problem physics and the model complexity weighed against available computational resources. Several issues must be considered in the development of an efficient multidisciplinary analysis code that includes nonlinear CFD solutions. These nonlinear solutions are obtained as a succession of linearized solutions (iterations); interaction with other disciplines may be accomplished at the convergence of the nonlinear equations or possibly during the iterations that lead to convergence. These interdisciplinary interactions and discipline analyses may be achieved by using a single integrated code or by interfaced analysis codes; these codes are referred to hereafter as integrated or interfaced systems.

Interdisciplinary interactions occur in real time (dynamically) but are often modeled as the iterated, steady-state discipline solutions that are required to match interface or compatibility conditions. Thus, many nonlinear CFD solutions may be needed to achieve the interface matching. Borland [63] has defined a multidisciplinary interfaced system as *"a collection of programs or technical modules which have been connected through methods of passing information from one module to another, usually through data files."* That is, discipline analysis codes (essentially treated as black boxes) are interfaced, and usually linked over specific computer platforms. Some of the inherent advantages and disadvantages of interfaced versus integrated systems are discussed in Ref. 9. Examples of interfaced systems currently under development are FIDO [64] and the Boeing Commercial Airplane Group's Advanced Aeroelastic System [63].

In an integrated system, it is possible to solve the coupled systems of equations in one of two ways. The first is a single-domain approach, the other a domain-decomposition approach (not to be confused with the mesh domain-decomposition methods discussed in section 1.2.1 and again in the paragraph to follow; one decomposes the individual discipline equations, the other decomposes the physical domain of interest). The former has been attempted by numerous researchers, some of whom are Felker [65], Sutjahjo et al. [66], and Ghattas and Li [67]. However, for an integrated system that solves the disciplines in a single computational domain, ill-conditioning of the resulting coefficient matrix dramatically hinders the convergence of the coupled systems. The alternative is an integrated system that solves (or partially solves) the disciplines separately and matches the solutions at the boundary interfaces as depicted in Fig. 1.3. This is referred to as the domain-decomposition approach and does not suffer from the aforementioned shortcomings. Furthermore, it appears that integrated codes, which utilize the domain-decomposition approach, tend to be more efficient and portable than their interfaced counterparts discussed above.

The ability of the code to model realistic configurations with respect to both the physics and the geometry is a concern within the aerodynamics discipline. To accomplish this task, several CFD codes are readily available that solve the Euler and Navier-Stokes equations by using structured-grid domain-decomposition techniques (e.g., multiblock, zonally patched, or overlapped grids) or unstructured grid technology. Excellent candidate codes, into which other discipline codes can be integrated, include CFL3D [68], TLNS3D [69], and OVERFLOW [70] for structured grids and USM3D [71] and FUN3D [72] for unstructured grid solvers. The integration of OVERFLOW with a finite-element structural code has been performed by Tzong et al. [73]. Examples of this type of integration with USM3D have been reported by Cavallo [74], who coupled this solver with ELAPS [75] (which models the wing as a flat plate) to perform aeroelastic analysis, and by Bhat and Parikh [76], who are currently developing an unstructured grid module for ENSAERO with USM3D. Batina et al. [62] also developed an unstructured grid approach for unsteady aerodynamic and aeroelastic analysis, which has been applied to full three-dimensional aircraft and utilizes modal shapes for the bending modes.

Determination of structural deformations, as mentioned above, can be achieved via a modal shape method or by modeling the configurations with equivalent plates or finite elements. As noted by Guruswamy and Byun [77], however, the reduction in unknowns gained by the modal approach for isolated bodies is usually offset by the difficulty that is associated with determining modal shapes that accurately represent the full configuration. One does not encounter this problem with finite-element structural analysis; in addition, one can obtain detailed stress information about the system being studied.

Once deformations have been determined from the structural analysis, these deflections must be represented on the aerodynamic surface. Similarly, aerodynamic loads must also be transfer to the structural nodes. This aerodynamic-structures coordination has been an active research area recently. The simplest approach uses bilinear interpolation to transfer the disciplinary information across the interface boundary. This approach, commonly referred to as load-lumping, has been successfully used by numerous researchers [54-60,63,64,74,77-79]. An alternative to this procedure was first developed by Guruswamy and Byun [77], who introduce a virtual surface, based on Appa splines [80], between the aerodynamic surface and the structural finite-element mesh. This virtual surface is then used to transfer the structural deformations to the aerodynamic mesh, and the principle of virtual work employed to obtain the loads at the structural nodes from the aerodynamic analysis. In a similar fashion, Tzong et al. [73] introduces a virtual surface based on finite-element technology to transfer the deflections, and virtual work (reciprocal theorem) to obtain the structural loads. Samareh [81] demonstrates the ability to transfer interdisciplinary information across interface boundaries using Non-Uniform Rational B-Splines (NURBS) [82]. In Ref. 81, sample functions, such as a sine wave, are mapped via a NURBS surface onto aerodynamic grids and similar surface deflection are modeled. The emphasis of that work was to demonstrate that parameterization techniques, consistent with the CAD definition of the geometry, may be used to perform the coupling between the aerodynamic and structures disciplines.

1.2.3 Multidisciplinary Design Optimization

MDO is a process which has been utilized by industry for many years; however, more often than not it has been coordinated at another level independent of the individual disciplinary expertise. This process can be considered an *over-the-fence* approach to MDO where designs, and data for those designs, are produced at the disciplinary levels, then transferred up to another organizational level (thrown over the fence) where it is compiled, evaluated, and decisions made. As noted in Ref. 83, that following this procedure "*as the design process goes forward designers gain knowledge but loose freedom to act on that knowledge*." This drives the need to coordinate the MDO process at the disciplinary levels where more *revolutionary*, as opposed to *evolutionary*, design improvements can be made. Recommendations on how this flow of information can be used to reduce the cycle time associated with the design and development of aircraft have been proposed by Grose [84] and by Jameson [85]. These papers propose a re-engineering of the design process, where Jameson presents a case study conducted on the McDonnell Douglas MDXX.

Coordination of the MDO process at the disciplinary levels can be considered as the *theory* of MDO, as opposed to the *practice* of MDO described previously. The theory of MDO is an emerging new field which attempts to use numerical optimization techniques to develop improved and efficient designs to complex, interacting engineering systems at the disciplinary level. Detailed surveys of research being conducted in this area have been compiled by Sobieski [86,87] and by Sobieski and Haftka [88] and, once again, the reader is directed to these sources. As should be expected with a relatively new field of research, numerous techniques have been proposed to accomplish the required coordination between the disciplines. In an attempt to obtain a perspective on the various methods being explored, Cramer et al. [89], Balling and Sobieski [90], and Newman et al. [91] have developed a classification of these techniques. These classifications are based on the means by which the analyses of the disciplines, the procurement of sensitivity information, and the numerical optimizer are interacted.

The best known method of computing the sensitivity information between coupled systems is via the solution of the global sensitivity equations derived by Sobieski [92]. This system of equations, however, may sometimes be ill-conditioned and the memory requirements associated with the storage of the coefficient matrix may be prohibitive. The fact that the global sensitivity equations are ill-conditioned should be expected since, as discussed in section 1.2.2, the single-domain approach to the multidisciplinary analysis suffers from this problem. Alternative formulations have been proposed, for example, by James [93] and by Cramer et al. [94]. In particular, the methods proposed in Ref. 94 were applied to a one-dimensional elastic nozzle by Shubin [95] to demonstrate that by delaying feasibility until later in the convergence of the multidisciplinary systems, time savings could be produced. This type of procedure, termed individual disciplinary feasible approach, falls between the traditional multidisciplinary feasible approach (i.e., at each design iteration the coupled systems and their respective sensitivity analyses are solved to convergence) and the SAADO approach that permits disciplinary and multidisciplinary infeasibility during the design iterations and only satisfies the optimality conditions at convergence. The most prominent of the aforementioned methods to solve the global sensitivity equations has been the multidisciplinary feasible approach.

The logical, and thus the most prevalent, research in MDO using some form of the global sensitivity equations has been the coupling of the aerodynamic and structures disciplines. A representative list of the work which has been undertaken may be found in references 95-100. In each of these procedures, however, simplified models have been used to represent the disciplinary analyses; most notably for the aerodynamics. This is due to the fact that the aerodynamic analysis tends to be the most CPU demanding part of the MDO process in terms of both time and memory requirements Furthermore, the corresponding contribution from the aerodynamic sensitivity analysis is proned to ill-conditioning for nonlinear fluid equations [101,102]. As an example on the use of simplified fluid models, Grossman et al. [96] utilize the finite-element method to analyze the structure of a transport wing, but resorted to a vortex-lattice method (a linear flow model) for the aerodynamic calculations. This work was later extended by Rais-Rohani et al. [99] to include the additional discipline of controls for the aeroelastic tailoring of a forward-swept wing. Only the aeroelastic instability of wing divergence is considered in Ref. 99 and the configuration was analyzed at a subsonic, subcritical Mach number which was a limitation of the aerodynamic model chosen. Subsequently, Arslan and Carlson [100] performed the multidisciplinary sensitivity analysis using the transonic small-disturbance potential equation for the fluid model and an equivalent flat plate model for the structure. The use of this simplified nonlinear fluid model allowed computations and sensitivities to be evaluated in the transonic regime. The resulting ill-conditioned global sensitivity equations were reformulated and solved by the incremental iterative technique mentioned previously. Furthermore, the work of Ref. 100 demonstrated the need for multidisciplinary sensitivity analysis, within the design optimization process, by showing that the sensitivity information produced by an aerodynamic-only calculation had different magnitudes, and in some cases different signs, from that obtained with the coupled sensitivity analysis. Similar findings have been reported by Barthelemy and Bergen [97] and by Newman et al. [78].

1.3 Objectives of the Present Work

Over the last half century, through relentless experimental and computational studies, resourceful design engineers have produced near optimal aerospace configurations. To further improve these designs, where the margin for improvement is small, designers will require additional information such as sensitivity derivatives. This additional information may also be used to expedite the design of new engineering systems for which there is no vast experimental or computational data base. These needs are the impetus for the development of efficient and accurate multidisciplinary analysis and sensitivity analysis procedures. To maximize the benefits of these procedures, they must have the capability of resolving both the physics and the geometric complexities of practical configurations.

Utilizing a divide-and-conquer strategy, the development of an integrated MDO procedure, capable of analyzing the nonlinear fluid flow about geometrically complex configurations, may be decomposed into the following three steps: (i) develop a procedure to perform the aerodynamic shape sensitivity analysis and optimization, (ii) develop the ability to perform the aeroelastic analysis, and (iii) develop a procedure which couples the aerodynamic and structural sensitivity equations to perform the aeroelastic design optimization. In the current work the first two of these three steps have been accomplished. For the first step, as depicted in Fig. 1.2, the aerodynamic analysis and the corresponding shape sensitivity analysis, are performed on unstructured grids. Discretization of the fluid domain with this technique permits the investigation of extremely complicated geometries. To allow for the modeling of flow fields in which nonlinearities (such as shock waves) may be present, the Euler equations have been chosen. Accomplishing the task of computing discrete sensitivity derivatives for these equations required the use of novel computational methods. The second step illustrated in Fig. 1.3, was to develop the capability to accurately account for the multidisciplinary interactions. To accomplish this, the aforementioned aerodynamic analysis code was coupled with a structural finite-element method. This enabled the ability to perform static aeroelastic analysis. Parameters are introduced to control the interaction of the computational fluid dynamics and structural analyses; these control parameters permit extremely efficient static aeroelastic computations. Thus, the fruit of the present research has been the development of a functional aerodynamic sensitivity analysis procedure capable of performing the shape design optimization of geometrically complex aerospace configurations, and the ability to perform extremely efficient static aeroelastic analysis. Applications of this procedure have been reported in references 13, 49, 50, 78, and 79.

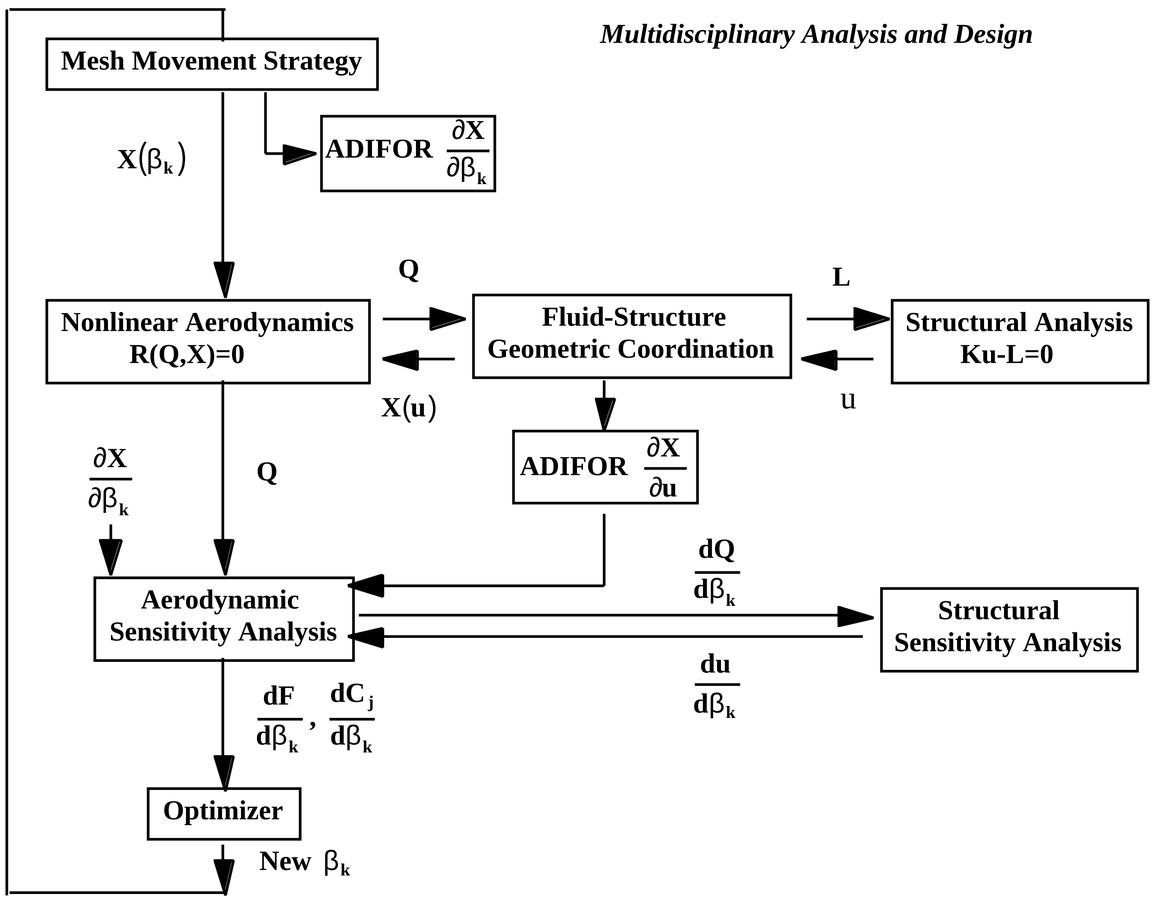

Figure 1.1: Integrated multidisciplinary design optimization.

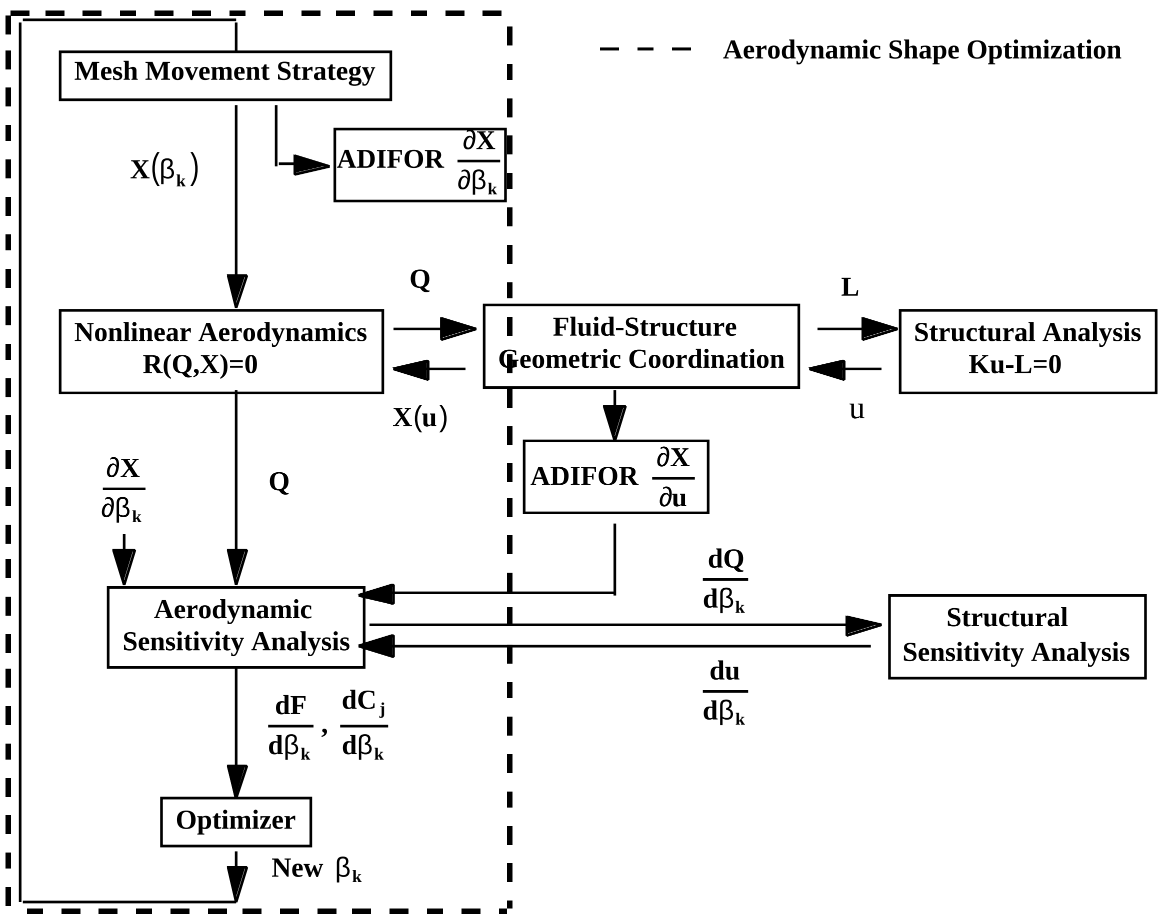

Figure 1.2: Aerodynamic shape sensitivity analysis and design optimization.

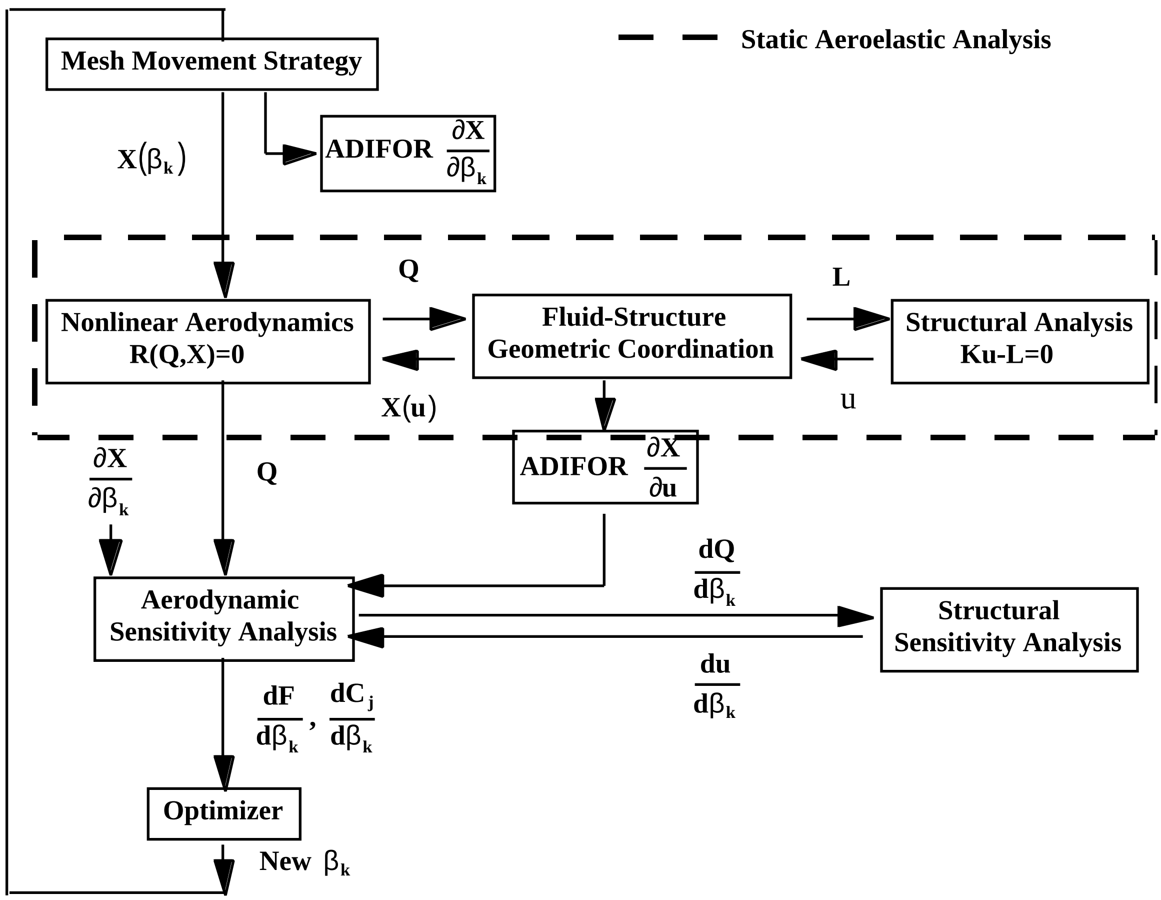

Figure 1.3: Static aeroelastic analysis.