Advances in Engineering Software 40 (2009) 479–486

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Parametric design of aircraft geometry using partial differential equations

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ARTICLE INFO

Article history:
Received 1 November 2007
Received in revised form 22 April 2008
Accepted 20 August 2008
Available online 20 November 2008

Keywords:
Aircraft design
Parametric design
PDE surfaces

ABSTRACT

This paper presents a surface generation tool designed for the construction of aircraft geometry. The software generates complex geometries which can be crafted or modified by the user in real time. The surface generation is based on Partial Differential Equations (PDEs). The PDE method can produce different configurations of aircraft shapes interactively. Each surface is generated by a number of curves representing the character lines of a given part of the aircraft shape that can be manipulated in real time. Different surfaces then blend to create the full shape of the airplane. An important function of the proposed tool is its ability to change the aircraft shape through the adjustments of parameters associated with the initial curves. The user can apply linear transformations to the curves generating the airplane through simple input from the computer keyboard and the mouse. The updated curves can then be used to generate the surface leading to different configurations of a given airplane shape. The work presents detailed descriptions on the PDE method, parametric design and manipulation of aircrafts along with graphical demonstrations of its abilities and a series of examples to illustrate the capacity of the methodology implemented.

1. Introduction

The growth of computer hardware and the progress of computational algorithms over the last few years have given us new alternatives for creating airplane geometry. Complex and time consuming computations are now affordable and they are easy to use through the present Computer-Aided Design (CAD) packages which provide various tools for parametric design of complex geometries and surfaces in general. Current CAD packages utilize parametric design by linking dimensions and variables to geometry in a way such that when the values change the shape of the object change as well. Thus, design and modification of an object or a group of objects can be performed very fast and in real time. It is also very common to represent surfaces in terms of polynomial functions of two parameters. The polynomial based methods used in CAD depend on the type of polynomial chosen.

Examples of such surfaces are: Bezier surfaces [1], B-Splines [2], Rational B-Splines [3] and Non-uniform rational B-Splines (NURBS) [4]. When using polynomial based methods the surface patch is usually generated using a set of control points, by manipulating these control points the surface shape changes. One problem that arises here is that the control points are usually too many, making it difficult to manipulate the underlying geometry. Thus, there is a need for developing techniques that allow the user to manipulate the surface effectively using minimum number of controls.

One of the major tasks in the design phase of a new aircraft is the definition of its configuration along with the main geometric characteristics. Present CAD packages provide several tools for the parametric description of complex geometries and surface definition is usually accomplished by utilizing such CAD systems. For an aerodynamic early phase conceptual design, a step before the application of CAD is needed, i.e. a toolbox that will produce generic and parameterized aerodynamic surfaces, which will take into account the special needs and constraints for the conceptual design of an aircraft. Besides the well known general CAD packages, very few are specialized in aircraft design. Below we highlight some of these.

Klein and Sobieczky [5,6] present examples of aerodynamic design of high speed airfoils and wings which is carried out by their Genetic Algorithm software. They use explicit functions, called basic functions to describe curves needed in the design of aircraft surfaces. Their goal is achieved by establishing a flexible input data generator for both direct and inverse design. The geometry and flow quality are modelled by a set of analytical functions with parameterized input. For communication purposes with CAD packages, the resulting surface is interpolated using NURBS surfaces.

A surface generation software named Generic Parameterized Aircraft Surface (Ge.P.A.S.) developed by Sarakinos and Valakos [7] is also designed for the construction of aircraft aerodynamic surfaces. The surface generation procedure is parameterized and different aircraft configurations can be produced in an interactive manner. The surface generation procedure is based on the use of NURBS curves and surfaces. Fuselage type surfaces are constructed

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doi:10.1016/j.advengsoft.2008.08.001

inside a scalable reference volume, where common basic curves in successive parallel planes are transformed to form the corresponding cross sections. Wing type surfaces are constructed in a more straightforward manner, using standard formulations for wing geometry definition and a database of wing sections to select from.

A number of numerical and experimental tools have been developed at the Department of Aeronautical Planning and are devoted to aircraft design for low subsonic flow [8]. These tools comprise numerical codes for analysis, design and simulation, experimental tests and are particularly oriented to light aircraft design. The user also has the choice of virtually flying the aircraft that is being designed using an interactive platform flight simulation.

The work entitled "Aircraft Design Support using Knowledge Engineering and Optimisation Techniques" [9] is an example of parametric airplane modelling showing that a proper combination of object oriented programming, rule based instantiation of objects and a geometry engine allows parametric modelling in the optimisation sense. The principle and implementation of High-Level Primitives (HLPs), i.e. functional building blocks, known as Multi-Model Generator (MMG) has proved to be a good approach to the problem of parametric modelling of complex products. It is also shown how these parametric models can be used and initialized in Design and Engineering Engines (DEEs). A DEE facilitates initiation of design parameters and variables, instantiates HLPs and creates Multiple Models to support the required multi-disciplinary perspective on the system as required in multi-disciplinary analysis and optimisation. DEE offers a framework for design decisions in the conceptual design phase.

Multi Model Generator (MMG) is another knowledge-based parametric tool for reproducing a conventional aircraft [10], whose purpose is to introduce the MMG into a dedicated Design and Engineering Engine (DEE) for performing load calculation in the preliminary design phase. For this purpose, MMG has to be capable of supplying different models of the same product, i.e. structure, mass and aerodynamic models in order to feed a set of analysis tools. The generated models are extracted from a Knowledge-Based Engineering (KBE) product tree, which is capable of holding the knowledge of the complete aircraft product. The definition of the aircraft is fully parametric so that consistent models for the different disciplines can be generated for a large variety of aircraft configurations by varying a single input file. In this case, the aircraft is modelled as an assembly of components, which in turn is built up as an assembly of high-level primitives.

RAGE [11] is another package that has been designed for the generation of aerodynamic models, where central parameterized geometry definition has been used. It is used at the preliminary stage of aircraft design for preliminary parametric studies and optimisation. Designers can develop aircraft geometries that vary from very simple to quite detailed ones for analysis with an assortment of computational aerodynamics tools in a very fast manner. Aircrafts are designed with the use of fuselage, wings and nacelle components which are available in the software. Each component is generated by a number of subcomponents that define the geometry. RAGE is able to output files that are compatible with several aerodynamic analysis codes and is compatible with most of the major CAD packages.

RDS-Professional [12,13] is an aircraft design and analysis program suitable for conceptual design and trade studies, technology evaluations, and preliminary performance predictions. It also supports 3D design and incorporates analysis modules for aerodynamics, weight, propulsion and cost. The software automates classical techniques for aircraft design used in industry as well as computational tools that perform trade studies and early stage optimisation. Aircraft geometry is produced using lofting techniques interactively, whilst aircraft components are designed using geometry parameters possessing some physical meanings.

The method that is being used in this paper for the construction of airplane surfaces is the so called PDE method [14,15]. Unlike spline techniques, the PDE method can produce complex surfaces in terms of a small set of design variables or parameters. The shape of the surface is defined through boundary curves and a small set of design parameters, taking a boundary value approach to the problem of surface design. This approach also allows the design system to be extended so that the functionality of the object can be taken into account at an early stage of the design process. Additionally, it has been shown that the use of the PDE method can significantly reduce the computational cost associated with the process of designing and optimising the performance of either a given airplane or specific components such as wings [16,17]. Here, the optimisation of the airplane geometry takes advantage of a small set of design parameters required by the PDE method to define complex geometry. Thus, using a small geometry parameter set it is possible to optimise the shape of an aircraft automatically in a reasonable time scale. For example it is possible to automatically compute a shape which minimises lift or drag.

The aim of this work is to discuss the advantages of using the PDE method in modelling airplanes in contrast with the use of other existing methods and to show how airplane surfaces with more general boundary conditions can be constructed and manipulated in real time. Additionally, the authors aim to demonstrate that this technique is capable of representing and manipulating an already existing geometric model of an airplane without any prior knowledge on the part of the designer regarding the mathematical details of the PDE method itself. For the purpose of explaining the use of the PDE method in airplane design, we will use examples illustrating the various designs, transformations and modifications of airplane models. All the examples presented throughout this work have been created interactively in real time.

The rest of this paper is organized as follows. Section 2 describes the mathematical details behind the PDE method and the solution in its standard formulation. Section 3 explains how the PDE method can be used to create a generic aircraft shape. Details are also discussed on the parametric representation of the airplanes and how to control aircraft shapes through adjustments of parameters associated with the curves. Section 4 contains examples and demonstration of various shapes of aircrafts using the proposed software and finally the conclusions of this work are presented in Section 5.

2. The PDE method

The boundary value approach based on the PDE method can be summarized mathematically in the following manner. Let $X(u,v)$ be a function defining a surface in 3D space in a domain Ω (with boundary $\partial\Omega$, on which some boundary data is specified).

Here u and v represent the parametric coordinates of a point in Ω, and $X(u,v)$ as a mapping from that point in (u,v) to a point in 3D space such that $R^2(\Omega) \rightarrow E^3$. We regard X as the solution to a partial differential equation of the form

$$\underline{X}(u,v) = (x(u,v), y(u,v), z(u,v)) > \tag{1}$$

Thus, the full problem consists of finding the solution to a set of three PDEs, one for each Cartesian coordinates (x,y,z) where a is an intrinsic parameter.

$$\left(\frac{\partial^2}{\partial u^2} + a^2 \frac{\partial^2}{\partial v^2}\right)^2 \underline{X}(u,v) = 0. \tag{2}$$

A wide variety of methods exist for finding the solution of elliptic PDEs similar to that shown in Eq. (2). These include elementary separation of variables, Green's Functions, and sophisticated