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Knowledge Based Aerodynamic Optimization

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Abstract

Software for aerospace vehicle surfaces is applied and further developed as a Parameterized Geometry Preprocessor suitable for aerodynamic design and optimization. Airfoil families are designed with knowledge based parameters and their variations are used for optimization strategies, as well as with spanwise parameter variations to shape arbitrary lifting wings. Integration with fuselage results in a one-block surface grid for wing-body configurations which is found practical for rapid prototype design. Generation of scalar distributions along surface gives target pressure functions to support the input of inverse design codes. Case studies derived from the NEXST supersonic transport project and other concepts illustrate the value of this approach.

1. Introduction

Aerodynamics is considered a mature engineering science. In this situation it is a challenge to focus on problems which still do not allow for a satisfactory solution using computational or experimental techniques. Computational analysis with the task to simulate the flow past aircraft configurations has come very far and impressive results are obtained with the help of high performance computers and fast numerical algorithms. At the same time experimental verifications are carried out in scaled flight tests, avoiding many of the inherent disadvantages of wind tunnel technology. In this situation we may ask, what is left to be done for aerodynamic research, besides its integration in a larger, multidisciplinary approach where aerodynamics is only an initial and certainly important, though relatively small part of the whole development process leading to such a complex project like a new high speed transport aircraft.

In this situation we observe that the computational tool boxes still may be better adapted to the special problems posed by flow physics, by suitably parameterizing the variables for data generation. In the present context of high speed aerodynamic shape design this means that formulation of the mathematical model boundary conditions is linked directly to the technical shape definition for usage in the other disciplines like structural design, to name only the most important partner of aerodynamic design. With such coupling needed we observe that data definition and its usage for numerical analysis is still the slowest part of the design process. The idea is therefore to learn from theoretically derived model problems how parameters are suitably selected in order to accelerate the design process. In high speed aerodynamics our classical knowledge basis includes airfoil and wing theory in compressible flow, this is therefore a starting point in this paper, pointing out that geometrical and flow parameters are connected in model problems so practical approaches should be laid out in a related way even when no more simple solutions are possible. From there we make full use of graphic and interactive tools on PCs and other relatively small computers, to obtain data prior to the use of commercial CAD programs, by a „Parameterized Geometry Preprocessor“, (PGP).

The present workshop is aimed to summarize computational efforts related to the Japanese supersonic transport „NEXST SST“. The author is grateful for a past short, but instructive collaboration with Japanese partners [1] in order to further develop and test the PGP software. First applications were reported in an earlier workshop, the author presented his methods to generate boundary conditions for numerical simulation of high speed configurations [2]. A small project was agreed upon between the partners to improve numerical tools and study the applicability of the author's geometry definition tool for a numerical inverse design code developed at NAL and based on Takanashi's concept [3]. This presentation now is intended to illustrate progress in PGP development since then and show options provided for the inverse design approach and other applications. Here it seems appropriate to use the NEXST wing geometry data, in the status of the past collaboration, to illustrate how configurations are made variable with few parameters for further design modifications and optimization efforts.

2. The Knowledge Base

Three decades ago the reporting of analytical results for airfoil shapes and their pressure distribution in high speed flow were welcomed by developers of early numerical algorithms to simulate inviscid flow. A key element of usefulness was the hodograph formulation which allowed to see the model problem in complete symmetry between geometry and variables of state, i. e. the velocy distribution surrounding the boundary condition. Wellknown case studies in closed analytical formulation still serve as test cases for CFD code development and the understanding of detailed aerodynamic phenomena in the transonic regime, see [4].

The supersonic regime is characterized by its downstream influence of geometry parameters, as hyperbolic potential theory teaches us. This results in suitably defined wing or cross sections, contrary to subsonic design techniques derived from classical mapping theory supported by elliptic potential equations, where all details of a boundary influence the flow at any point.

These wellknown facts and other mathematical characteristics have strong influence on suitable and practical geometry definition, manifest through various typical parameter choices to calibrate airfoils or body cross sections.

3. Airfoil parameters

Based on mathematical structures of analytical results for the abovementioned model flow equations, a number of key parameters have been defined which not only drive aerodynamic performance very effectively, but also are simple technical details of the resulting airfoil. The variability of these PARametric SECtion („PARSEC“) airfoil families to be generated is huge, as has been found by many users. Basic sets with only 11 parameters [5] allow already for many useful airfoil shapes, as can be tested from a public version of an interactive code, see the „PARSEC Airfoil Generator“ in the web site [6]. With various aerodynamic refinements requested by design projects, we have added additional camber control for reflex airfoils, surface bumps for viscous interaction control in transonic flow and divergent trailing edge models for circulation control, resulting in about 30 parameters total [7]. New interactive versions using these parameters are aimed as tools for airfoil optimization, employing rapid CFD analysis like the MSES code. Figure 1 shows the user surface of an option with 14 input parameters as found useful for supersonic wing sections as will be seen from an SST wing redesign example.

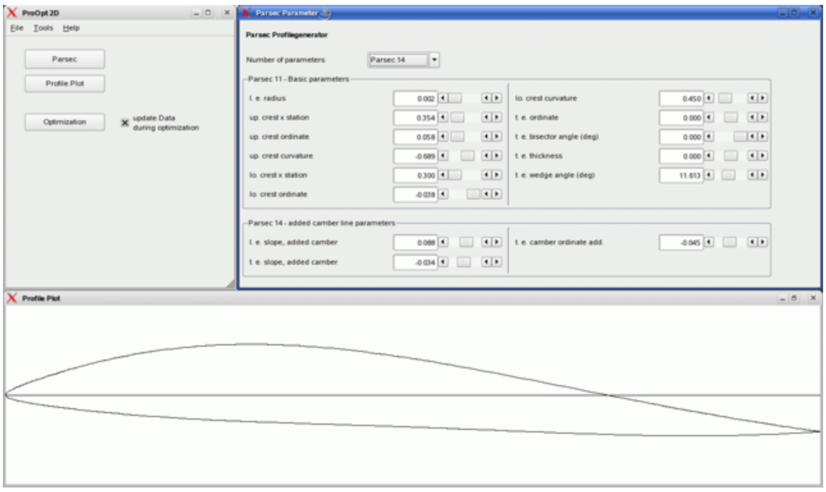

Figure 1. PARSEC interactive code for numerical airfoil optimization [8]
Optimization for geometry modeling with target pressure distribution using rapid CFD analysis.

4. Parameterized pressure distributions

As mentioned above, the early model equations suggest a symmetrical treatment of geometry and flow parameters, resulting in either direct analysis of given shapes, or inverse design to obtain shapes with a given aerodynamic performance. For practical case studies, both geometry and target pressure distributions are defined by a limited set of parameters guided by the most efficient concepts to influence the phenomena. For transonic flow this is a strong control of local curvature distribution in areas with local sonic and supersonic Mach numbers. For viscous interaction control this is an option to modify the trailing edge geometry corresponding to a desirable local pressure gradient. For precise inverse techniques the leading edge curvature distribution has to correspond to target pressure distributions including a stagnation point - otherwise such methods will require correctures to arrive at closed contours and other non-physical results.

Figure 2 shows geometry data for a 2D airfoil plus a pressure distribution model to be used as a target function for the airfoil to be modified. An optimization code [8] is operational accepting this dual input, allowing adjustment of the given airfoil to accomodate the pressure model, or create input for various analysis codes to find a pressure distribution for the airfoil and its variations.
A straightforward extension is the definition of swept wings along with spanwise pressure distributions to have input for 3D analysis and optimization strategies as outined in the next chapter.

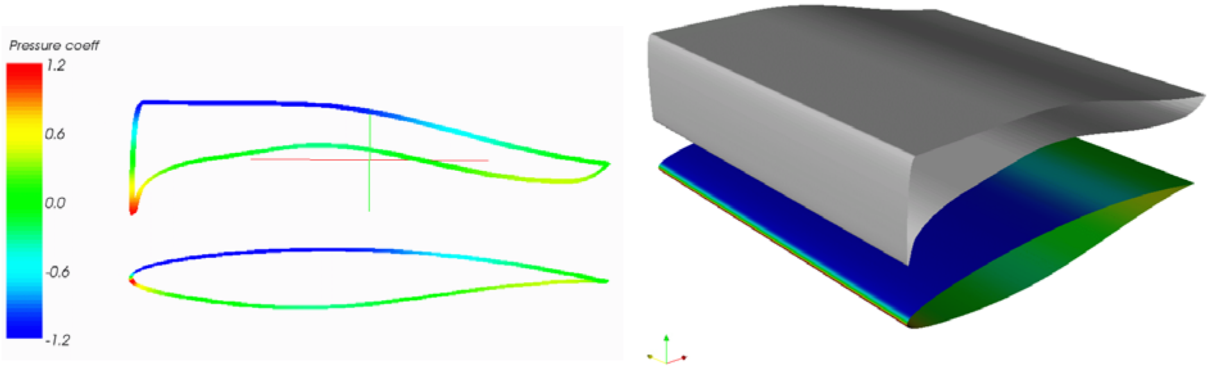

Figure 2. PARSEC airfoil and PARCPX pressure distribution
Combination of geometry and surface scalars: Definition of target surface pressure coefficient as a geometry. Extension from 2D airfoil to 3D wing surfaces.

5. 3D wing geometry and surface scalar generation

As depicted in Fig. 2, a spanwise extension of the 2D airfoil section along with en extension of the generated surface scalar is straightforward. In this case arbitrary wing surfaces with target surface pressure definition can be defined if the parameters for geometry and for the scalar are suitably varied along the third dimension, the spanwise direction. Airfoil data are scaled and fitted within defined shape of leading and trailing edge in 3D space, this way allowing a controlled variation of wing section geometry plus a projected target pressure distribution on the surface. Clean wing flows without interfering fuselage and other additions to the configuration are only a very first approximation of real aircraft flows, we therefore will have to create full configurations for computational analysis and design. An improved boundary condition for design purposes is a fully integrated wing-fuselage combination. Usually we need CAD software to combine surface components including fillets at the wing root emanating from the body. With the wing parameters in good control by spanwise variation of the PARSEC parameters, we use another method to create parameterized wing-body combinations:
The wing planform, as it is basically described by spanwise definition of leading and trailing edge, is extended toward the plane of symmetry, approximating the body contour roughly. Blended wing configurations are ideally modelled this way: The inner wing sections are housing the loaded area. For conventional body shapes consisting of more or less circular or elliptic cross sections a deformation of the inner portion of densely defined 'wing' section coordinates in the cross sectional plane is needed to arrive at the desired body surface. With suitable blending functions this process can smoothly be integrated with the outer, unchanged wing coordinates.

6. Case Study based on the NEXST SST geometry

In a short cooperation a few years ago between German and Japanese aerodynamic research institutions the above illustrated techniques have been applied for practical use in realistic aircraft geometries [9]. The project goal was a combination of the geometry tool as illustrated here, with Takanashi's [3] inverse design code, applied to the wing of a supersonic transport aircraft „NEXST“, Japan's project for a successor of the Concorde. One initial exercise was the redefinition of wing surface data resulting from Takanashi's code, by modeling the given wing surface as close as possible by PARSEC airfoils but in addition arriving at spanwise smooth surface data which the inverse code did not provide. Figure 3 shows the given wing surface, the given and the redesigned sections at some span stations and finally a plot of sections at wing span stations distributed densely along the redefined wing surface. Similar to the PARSEC functions, each one of the parameters is modeled by a spanwise analytical function of the wing geometry generator approximating the coarse and non-smooth values at 15 spanwise support stations which have been extracted from the given section data. This one-time manual procedure is replaced in a computational optimization process if the initial wing is already modeled by this generator: Inverse analysis delivers the geometry correction data which are directly evaluated for parameter change.

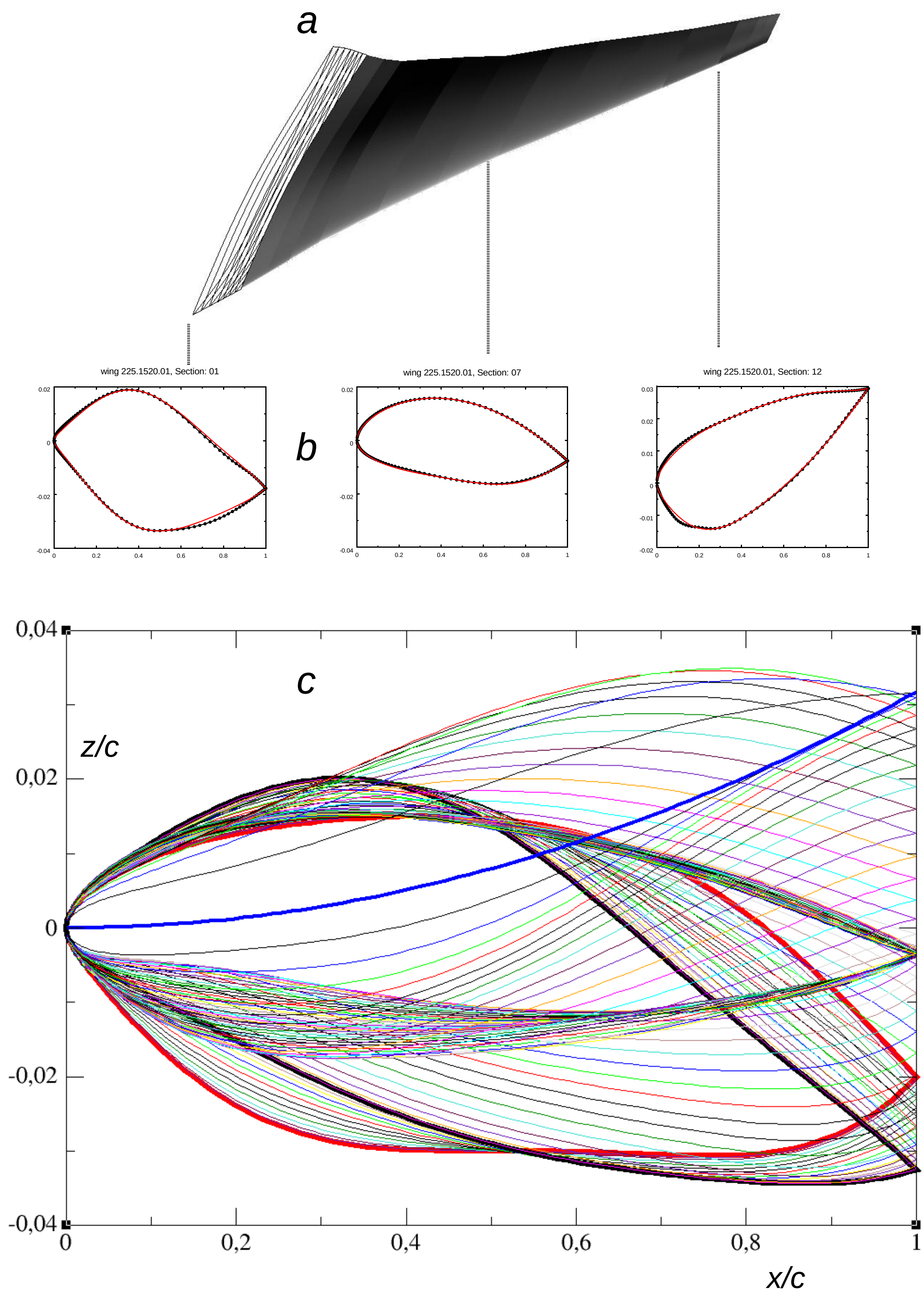

Figure 3. Geometric redefinition of the NEXST SST wing surface
Initial wing surface resulting from inverse design code, with 15 given sections, (a).
Section representation by PARSEC-14 depicted for 3 selected span stations in comparison with original data, (b).
76 redefined airfoils in a blown-up scale to result in smooth wing surface guided by inverse design method., (c)

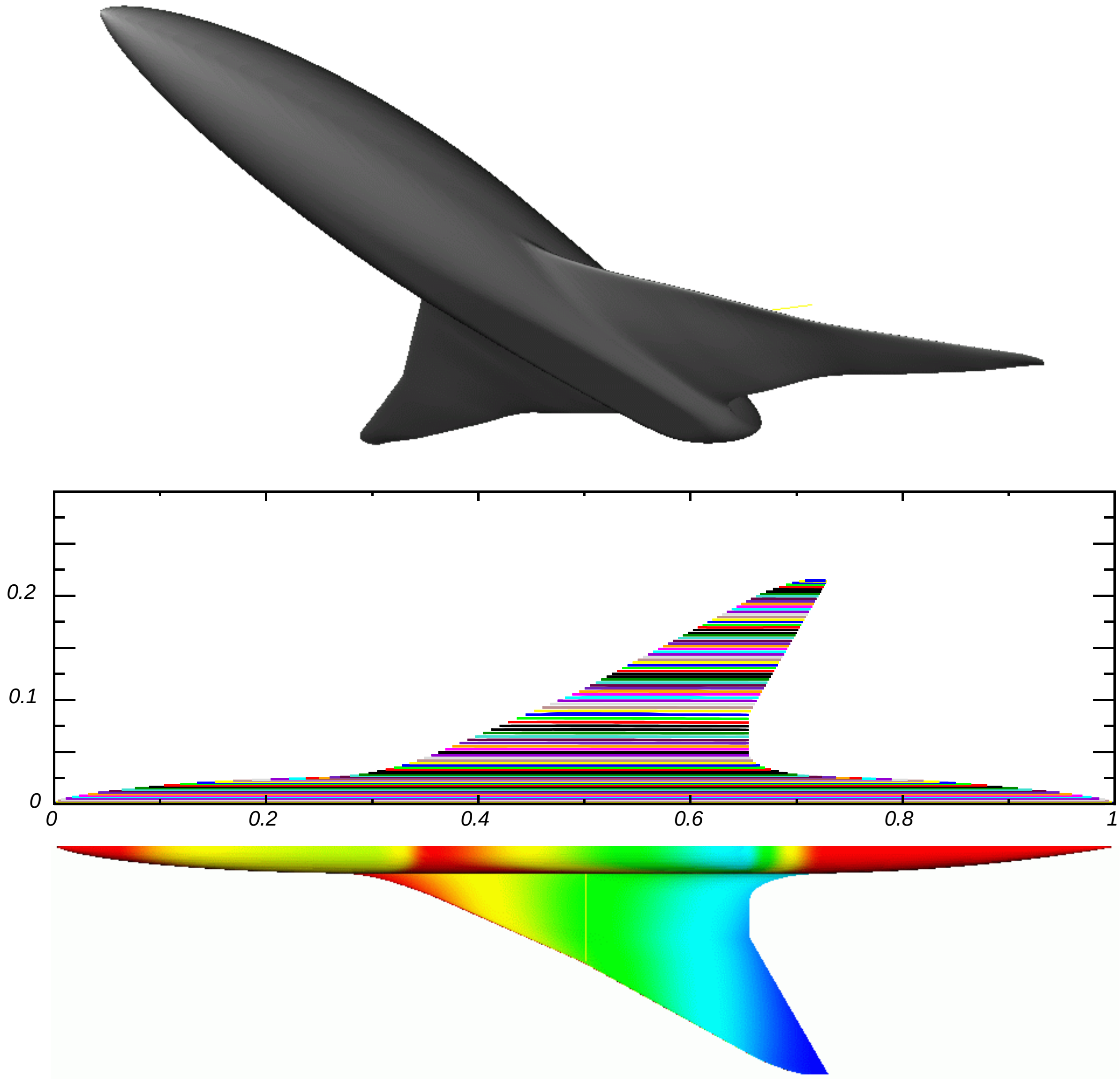

Figure 3. Wing-body configuration

A dense spanwise distribution of analytically defined PARSEC wing sections extends toward the center line. Within cross section planes coordinates are moved according to the body definition function. Blending the movement outside the body defines fillet geometry, complete surface consisting of wing, fillet and body is one block. Application of PARCPX scalar functions to model a pressure distribution, allowing for arbitrary surface pressure target, e. g. isobar concept or minimized spanwise pressure gradient for crossflow instability control.

7. Wing - Body configuration model with prescribed pressure distribution

The refined wing derived from NEXST data was used for further development of the parameterized geometry preprocessor. Guided approximately by NEXST body dimensions the wing planform is extended to body contour. Analytically prescribed body surface geometry functions are suitable for knowledge based parameterization of the body:

Cross section variation of the body based on the Supersonic Area Rule and area distributions guided by the Sears-Haack body of minimum drag are simple defaults established in the analytical code used here.

Scalar distribution generation on the wing surface is guided by the knowledge of pressure distributions favorably influencing the boundary layer. Design considerations in the NEXST project [1] gave ideas about calibration of the PARCPX parameters. Fig. 3 shows a color coded illustration of a pressure distribution resembling the one observed on the upper wing surface from CFD simulations of the NEXST wing-body configuration.

8. Data for CAD and CFD

Aside from suitability of PGP for inverse design techniques, a main purpose of PGP generated surfaces is to provide input data for commercial CAD programs as these allow for preparation of most of the subsequent computational and experimental steps needed to carry on the project. Multidisciplinary investigation need a common data base in a commonly understood format which is usually the iges format. CFD grid generation software requires CAD generated data and numerically controlled model production needs these also. One important feature of the preprocessor, therefore, is the data output in compatible formats, at least to provide input for our own CAD software available for various project tasks.

At DLR, CAD software (Argon, Catia) is used and PGP generated data are read and processed.

Airbus (UK) has received our PARSEC airfoil code with 29 parameters for inclusion in their Catia source code, which allows usage of the well developed user surface and combination of aero-knowledge based tools with Catia's other powerful options.

Several other case studies are under way to improve the PGP. One other concept for SST is the Oblique Flying Wing (OFW), which is attractive for future studies because of its excellent aerodynamic efficiency; it has also been subject to data exchange within the joint DLR-NAL project [9]. More recent work with this geometry includes CAD data presentation to designer Frank Heyl [10], who used it as a case study proposing novel operation of such large aircraft in airports.

Another possibility to use this tool is an extension of geometry into the 4th dimension:

Unsteady configurations like (flapping) wings and rotors in turbomachinery and helicopters, furthermore the simulation of adaptive (moving) devices for in-flight optimization, toward what is called the „Morphing Aircraft" adjusting to required operation conditions: These are our future tasks.

9. Conclusions

Refinements of a geometry tool have been shown, motivated largely by aerodynamic design projects like the Japanese SST and guided by the aerodynamic knowledge base which allows the choice of a limited number of efficient geometric design parameters. The analytical explicit functions used to create surfaces make this tool extremely fast which seems necessary for large optimization loops expected in multidisciplinary applications. Interfaces with commercial CAD software have been provided and various case studies for configurations in all Mach number regimes are possible.

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