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Enhancement of CEASIOM with Rapid-Meshing Tool for Aircraft Conceptual Design *

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1. Introduction

Computational Fluid Dynamic analysis for the aerodynamic characteristics determining performance, stability, handling qualities, and control effectiveness is a vital part of modern aircraft design. Many CFD tools exist for this analysis but their application to the earliest phases of aircraft design is currently limited by the time it takes to perfect the conceptual geometry model and then create a computational mesh of sufficient quality to have confidence in the computed results. Historically, high-fidelity grids of a new design concept were not expected until months or even years into the design development process. Designers would neglect the finer details of surface arrangement and intersection, yet to be defined, as they focused upon their real job, the design integration of a workable and optimal vehicle concept.

The RDS Professional software 2 developed by Conceptual Research Corporation is a well-known tool for conceptual aircraft design. Tailored to allow the designer to develop a new concept or modify a previous baseline design, its proprietary Design Layout Module (DLM) permits rapid aircraft configuration layout by mouse-driven interactive computer graphics. The RDS-DLM geometry uses its own unique format DSN [1] consisting of components defined by either stored surface points or modified parametric Bezier curves (NURBS subset). Each component is intended for production-quality lofting, so its model can not be meshed without additional refinement.

The CEASIOM3 (Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods) environment is developed to provide computational analysis of a wide class of aircraft at a very early stage of design. It is meant to support engineers in the conceptual design process of the aircraft, with emphasis on the improved prediction of stability and control properties achieved by higher-fidelity methods than found in contemporary aircraft design tools. One of the primary driving forces behind the development of the CEASIOM environment is to facilitate early computational analysis of highly novel aircraft concepts at a very early stage of its design. CEASIOM consists of a set of tools which allow the user either to generate from initial templates, or to import, a wide range of aircraft concepts and then use these to work through the design process generating the required aircraft parameters as they proceed.

CEASIOM requires an unified initial layout as input as the baseline configuration sized to the mission profile by specification of the $O(10)$ parameters employed in the pre-design loop. Then it refines this design (in concept-design loop $O(100)$ parameters) and outputs it as the revised layout for consideration in the down-select process (say $O(1000)$ parameters) in...
Fig. 1. SUMO\textsuperscript{4}, integrated into CEASIOM as part of its geometry module, is being developed to handle CAD geometry from a variety of sources, including RDS Professional\textsuperscript{c}. It contains a fast mesh generator and generates unstructured volume grids automatically with the tetrahedral mesh generator TetGen\textsuperscript{5}. The sumo (with TetGen) produces the simplified CAD ($O(100)$) parameters in Fig. 1, used for inviscid compressible CFD.

CEASIOM has its geometry construction system - AcBuilder (Aircraft Builder), to create and visualize its initial layout. It supports lifting surfaces, fuselages, tail booms, fairings, pylons, nacelles, and integration of engine intakes and nozzles and is award of control surfaces such as ailerons, elevators, rudders, flaps, slats, and all-moving surfaces. To accomplish the whole “virtual-aircraft design” loop, CEASIOM could do the job alone, referring to [4] pp. 10-11. A main advantage of coupling RDS with CEASIOM in the geometry design stage, is that the RDS-DLM can provide more geometric details than CEASIOM-AcBuilder. For example, it is no way to create an n-section-wing aircraft by using AcBuilder. As Fig. 1 shows, the RDS geometry corresponds to the simplified CAD, while AcBuilder provides the very basic geometry parameters employed in the pre-design stage. Turning the RDS model into a solid model with little inaccuracies during process would save the efforts when “re-design” occurs. The rapid-meshing tool could provide qualified mesh and thus make an enhancement of CEASIOM.

Figure 1. Varied levels of geometry from pre-design to detailed-design, where RDS geometry corresponds to the simplified CAD.

Note that the RDS geometry is not intended for production-quality lofting, so its model can not be meshed without additional refinement. To get a meshable model from RDS geometry, a RDS-SUMO interface is developed. It reads the RDS-DLM DSN file and writes the SUMO SMX file. The volume mesh can be saved in the native format of the CFD solver EDGE [7] which computes Euler solutions in this paper and the fast and simple CAD geometry would be obtained from the interface Fig. 1. Although RDS can output geometry in the standard DXF format, the interface works directly from the RDS internal format to avoid an intermediate step which would add time and inaccuracies to the translation.

The interface links the RDS aircraft design software with CEASIOM, which is proposed for preliminary aircraft design, and provides variable fidelity CFDs and stability analysis in early design stage. Thus the ideas embedded in the RDS model become a “virtual aircraft” that can be analyzed and maneuvered by CEASIOM (Fig. 2). Once the virtual aircraft satisfies the engineer’s and the customer’s requirements, wind tunnel models could be built. The details of virtual aircraft design are spelt out in [3].

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Figure 2. Virtual aircraft design loop by RDS coupled with CEASIOM


\textsuperscript{5}A Quality Tetrahedral Mesh Generator and a 3D Delaunay Triangulator, http://tetgen.berlios.de/
2. From Lofting Geometry to Meshes

To illustrate how the interface works, two aircraft models are studied, which are designed and developed by Dr. Dan Raymer through RDS Professional. The qualities of the mesh are acceptable for solving Euler equations and the transonic properties would be captured when needed. Yaw stability is of great interest for both configurations.

2.1. Asymmetric aircraft concept

As a test case for the RDS-SUMO-CEASIOM process, an asymmetrical aircraft concept developed several years ago was employed [6]. With both tractor and pusher propellers, an offset fuselage, and an extra nacelle on the starboard wing, the design is a suitable stress test for a rapid meshing program. The RDS geometry was emailed from California to Stockholm, and after about 2 hours of minor modifications, a smooth geometry was ready for automatic gridding and CFD analysis including a simple propeller disk model [8]. Figure 3 presents the SUMO meshable model of the concept, and the automatically generated tetrahedral volume mesh with 9 million cells for solving the Euler equations.

Since it is essential to include the propeller-thrust effects in the aerodynamic characteristics, the aerodynamics was computed by Euler EDGE. Potential-flow methods such as vortex-lattice or panel cannot easily model the momentum source. The propeller is simulated as a “very short” nacelle in SUMO-CEASIOM-EDGE. Specification of (the same) mass flow into and out of the disk adds a momentum that provides the pressure jump, but the mass flow model cannot account for finer details such as the swirl in the propeller slipstream. The propeller thrust was chosen to balance the cruise drag. Fig. 5 visualizes the streamlines in the flow accelerated by the propellers.

Figure 2.1 shows $C_L$ and $C_m$. The very cambered Natural-Laminar-Flow airfoil has extremely high lifting slope [9] which makes the lift coefficient of the whole configuration marginally exceed the “ideal” flat plate lifting slope $2\pi$. Figure 2.1 shows stick-fixed stability in both pitch and yaw, $C_{m,\alpha} < 0$ and $C_{n,\beta} < 0$.

EDGE calculates the aerodynamics of control surface deflection by the transpiration boundary condition, with flow tangency to the deflected surface prescribed on the undefflected surface. This method avoids mesh deformation, so one mesh can be used for all the deflection cases. However, it doesn’t work well for large deflections.

The asymmetry might cause serious control problems especially when the front engine fails and the analysis focuses on yaw trim and stability. For low speed and small side-slip angles, the aerodynamics follow a linear trend. The analysis predicts that to fly with a sideslip 3 degrees nose-left, the rudder needs to deflect around 8 degrees to left to trim.

The failure of the front engine would make yawing more serious since more thrust comes from the single pusher propeller. Figure 5 presents the streamlines and pressure coefficient on the surface with front engine out. There are several immediate effects due to one engine failure. The initial effect is the yawing that occurs due to the off-center thrust which makes the aircraft drift to the dead engine, i.e., yaw to nose-left. The inherent directional stability tends to oppose the asymmetric yawing moment. “Yaw-induced roll” is a secondary effect which accompanies yawing motion due to the higher lift produced on the advancing wing. In this paper the asymmetric yawing moment is preliminarily considered and the balanced flight with rudder is proposed.

Table 1 shows the lateral coefficients for twin-prop
and one-engine-out flight. The right wing-mounted pusher provides more asymmetric force, that tends to yaw the aircraft to left (i.e., the dead engine). To fly at zero side-slip, a rudder deflection around 10 degrees is required compared with 1.6 degrees rudder deflections when two propellers are both working (Fig. 6). Such deflection required for trim is probably too high. Compensation for strong lateral gusts may need more yaw moment authority than is available when 10 degrees are used for trim, and rudder stall becomes an uncomfortable plausibility. There are two ways to reduce the rudder trim deflection and enhance its authority, one is to reduce (the absolute value of) the $C_n$ at $\beta = 0$, another is to increase the rudder efficiency $C_n, \delta$.

The rudder needs to be re-sized to counter the extra yawing moments produced during an engine-out event. The rudder is originally sized as 27.5% of the chord along the vertical tail. To get better or smaller rudder deflections, the rudder efficiency could be enhanced by either increasing the rudder fraction of the vertical tail, or keeping the rudder fraction while increasing the size of the vertical tail, so that becomes larger and trim beta becomes smaller. Both methods increase the force produced by the rudder. In this paper an attempt of rudder re-sizing has been made, by making the rudder 50% larger than the original size, i.e., 41.5% of the chord along the vertical tail. The new rudder shows better trimming properties, for example, to fly at zero side-slip, the rudder needs to be deflected 7° instead of 10° (Fig. 6).

The asymmetric flight would make the control more demanding and serious, whatever the working en-
Engine(s) is one or two. The best way to solve this problem probably is, to add another engine on the left wing!

Table 1
Lateral coefficients for twin-prop and one-engine-out mode

<table>
<thead>
<tr>
<th>mode</th>
<th>$C_n(\beta = 0)$</th>
<th>$C_{n,\beta}$</th>
<th>$C_{n,\delta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>-0.00221</td>
<td>-0.0028</td>
<td>0.0014</td>
</tr>
<tr>
<td>OEO</td>
<td>-0.01717</td>
<td>-0.0036</td>
<td>0.0017</td>
</tr>
<tr>
<td>OEO, larger rudder</td>
<td>-0.01717</td>
<td>-0.0036</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

Figure 6. Side-slip angle $\beta$ versus rudder deflection $\delta_r$ when trim in yaw

2.2. Tailless Chin-Rudder Aircraft

The study of tailless aircraft with chin-rudder, in Fig. 7, was funded by NASA future airliners “N+3” project. It was modeled based on Boeing 737-800 and with a design goal that obtaining a 70% reduction in fuel consumption. The Tailless design features with a retractable canard and an all-moving chin-rudder. The Open Rotor propulsion system mounted on the rear part of the fuselage seems to offer the greatest payoff in terms of engine specific fuel consumption [10]. The canard is extended at take-off and landing to counter the huge nose-down pitching moments created by the large wing flaps by adding lift for. During cruise it retracts to reduce drag by reducing the wing area. Control is provided by a combination of wing trailing edge surfaces, the chin-rudder and nacelle-pylon ruddervators. The all-moving chin-rudder is the primary responsible for yaw control, and CFD analysis is performed in this paper to confirm the sizing of the chin-rudder for yaw control.

The RDS-DLM module provides the wire-frame model that the rapid interface could turn it as a “solid” mesh on which the Euler equation would be solved. The process is automated without any human intervention. The sizes of the control surfaces and flaps are also specified as overlapped wings in the native RDS file and modeled in SUMO accordingly.

When the aircraft cruises at Mach 0.8 the transonic shock forms on the upper main wing and extends downstream until 75% of the local chord (Fig. 9(a)). To compare the results from Euler and classical DATCOM in RDS, the Euler gives $C_{L,0} = 0.155$ per deg while DATCOM gives 0.160 per degree. That calibrates the Euler analysis from the RDS geometry.

2.2.1. Chin rudder authority

The chin rudder is proposed to restore the moment in yaw, while the aircraft is suffering, for example, a lateral gust. It is also required to have sufficient authority to do the one-engine-out control [10]. While the nacelle pylon ruddervators could help produce yaw moment, in this study we use the chin rudder only for the yaw control during normal flight. This aircraft has inherent instability in yaw. However as long as sufficient control is attained, we could probably forget
Figure 8. RDS-SUMO rapid interface process: from wire-frame to mesh

The chin rudder is deflected for yaw moment control. The Euler solver shows that in order to balance a 3° nose left sideslip, the chin-rudder needs to be deflected 6° relative to the free stream [10]. Figure 9(a) shows the transonic aerodynamics, and Fig. 9(b) shows the Euler pressure distribution with a zoom on the chin-rudder. Note that the nose of the fuselage is a bit rough, resulting in pressure oscillations. In a more detailed study it should be smoothed out.

2.2.2. Canard action at take-off

The retractable canard is used for adding nose-up pitch moment when the large wing flaps deflect and retracts completely for efficient cruising flight. The canard flap is 28% of the chord, and the wing flaps are 26% of the chord, shown in Fig. 10.

The canard location at the nose makes the moment arm long enough to produce sufficient nose-up moment for take-off when both the inboard and outboard flaps are deflected 30 degrees producing lift and a pitch-down moment. The canard elevator is deflected 15 degrees down to counter the nose-down pitch and at Mach 0.242 gives an increment of 0.544 in $C_L$ and 0.708 in $C_m$ at $\alpha = 0$. Fig. 11 presents the pressure distribution. The low pressure regions on the wing and canard trailing edges due to flap deflections are obvious.

3. Conclusions

The CEASIOM software is to support engineers in many aspects of preliminary aircraft design. The RDS-SUMO interface rapidly produces grids for inviscid...
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Figure 10. Flaps on the surface mesh

(a) Canard flap

(b) Wing flaps, inboard and outboard flaps

Figure 11. Surface pressure distribution from Euler solution, $M = 0.282$, $\alpha = 0$, $\beta = 0$

compressible CFD to enhance CEASIOM’s capacities. The qualities of the mesh for the two test cases are sufficient that could provide an equivalent propeller model, and promising transonic analysis. The yaw trim for both cases are investigated for lateral stability & control. The RDS-SUMO rapid-meshing tool illustrated in this paper enables quick aerodynamic assessment of even radical new concepts in early stages of aircraft design. This opens the way to prediction of the flying qualities and 6 DOF flight simulation by e.g. the SDSA [11] module in CEASIOM.

REFERENCES