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The NASA Common Research Model: a Geometry-Handling Perspective

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The NASA Common Research Model (CRM) was conceived specifically to support applied Computational Fluid Dynamics (CFD) validation activities. Primarily because of its use during the AIAA CFD Drag Prediction Workshops (DPW), it has become the one of the most widely studied airframes in the world. However, while much has been written on the subjects of mesh generation and the predicted flow solutions, very little has been published concerning the manner in which the NASA CRM Outer Mould Lines (OML) have been supplied, or of the associated geometric pre-processing requirements for surface or volume mesh generation. In view of the challenges posed by geometry-handling in the context of aerodynamic simulation in general and of the recognised importance of geometry and mesh generation to the NASA CFD Vision 2030, this paper is intended to help address this gap in the literature. One of the geometry models supplied for DPW 4 - an open test case, familiar to many in the international community – is used to illustrate some of the difficulties that may be encountered when producing CFD-ready OML. By reviewing some of the underlying geometric principles, the material presented identifies some general challenges concerning not only the format, but also the form in which airframe OML should be defined for use with CFD.

Nomenclature

APGS	=	Aerodynamic Geometry Panelling System
BREP	=	Boundary REPresentation
CAD	=	Computer Aided Design
CFD	=	Computational Fluid Dynamics
CRM	=	Common Research Model
DPW	=	Drag Prediction Workshop
IGES	=	Initial Graphics Exchange Specification
MCAD	=	Mechanical CAD
NASA	=	National Aeronautics and Space Administration
OML	=	Outer Mould Lines
STEP	=	Standard for the Exchange of Product Model Data

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I. Introduction

The NASA Common Research Model (CRM), Figure 1, (Ref 1) was conceived specifically to support applied Computational Fluid Dynamics (CFD) validation activities. Primarily because of its use during the AIAA CFD Drag Prediction Workshops (DPW) (Ref 2), the NASA CRM has become the one of the most widely studied airframes in the world. Its utility has expanded far beyond its originally intended scope: for instance, in addition to fundamental validation per se (e.g. Refs 3-5), it has become a standard platform for evaluating a wide range of CFD-related technology developments – from mesh generation (e.g. Ref 6) to multi-disciplinary optimisation and analysis (e.g. Ref 7).

However, while much has been written on the subjects of mesh generation and the predicted flow solutions, very little has been published concerning the manner in which the NASA CRM Outer Mould Lines (OML) have been supplied, or of the associated geometric pre-processing requirements for surface or volume mesh generation. In view of the challenges posed by geometry-handling in the context of aerodynamic simulation in general (Ref 8) and of the recognised importance of geometry and mesh generation to the NASA CFD Vision 2030 (Ref 9), this paper is intended to help address this gap in the literature.

In contrast with the pre-processing challenges posed by the need to undertake CFD assessments of the aerodynamic performance of fully-featured airframe configurations, the complexities posed by the NASA CRM OML are minor and their resolution straightforward. The principal reason for reviewing them is to illustrate some of the difficulties that may be encountered when producing CFD-ready OML using an open test case that will be familiar to many in the international community. It is hoped that, in so doing, it will help provide a timely (Ref 10) clarification of some of the issues involved in CFD pre-processing and thereby explain some of the challenges facing the development of improved and increasingly automated numerical simulation process chains.

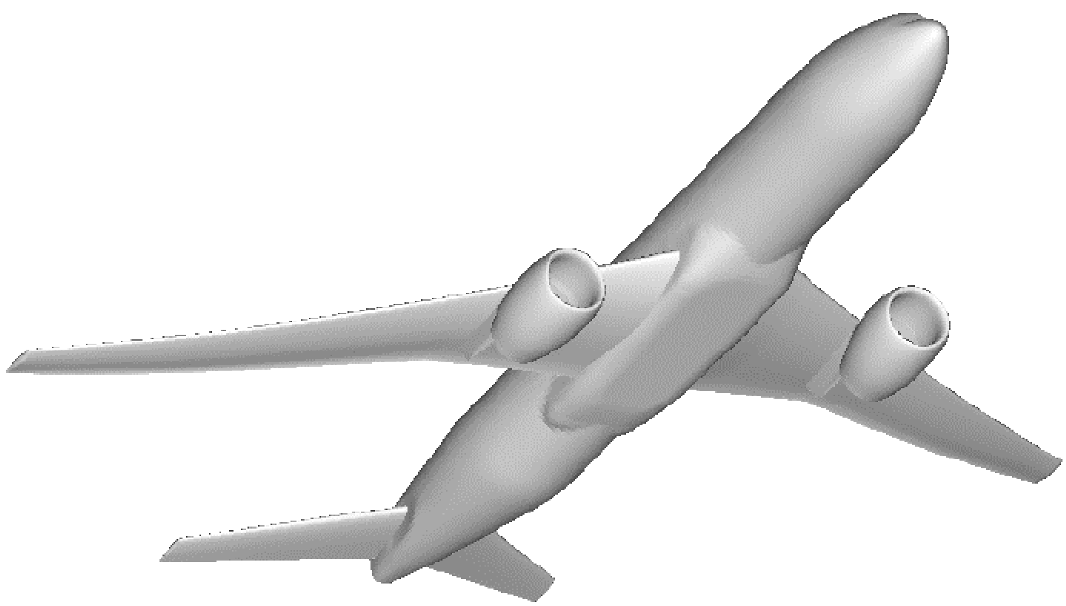


Figure 1. The NASA CRM Wing/Body/Nacelle/Pylon/Horizontal-Tail Configuration (Ref 1)

For convenience, the paper focusses on the geometry models supplied for DPW 4 (Ref 11) and subsequently re-used in DPW 5 (Ref 12). These do not include the nacelle or pylon. Moreover, since no two mesh generation tools are identical – and, consequently, details of geometry pre-processing requirements may vary accordingly - the intent is to draw attention to those aspects that are considered to be of more general applicability. A more detailed and systematic analysis, which ought also to include assessments of the various ways of generating the geometry models as well as the computational meshes, is beyond the current scope. The need for such an activity is one of the motivations for establishing an AIAA Geometry and Mesh Generation Workshop – the first of which is scheduled to take place in June 2017 (Ref 13).

II. Preparation of the Geometry Models

The conceptual layout of the CRM geometry was formulated through a discussion held during a NASA Subsonic Fixed-Wing Working Group, comprised of representatives from NASA, Boeing and numerous other US Aerospace Organizations. Based on the gross parameters of this conceptual layout, John Vassberg (Boeing) refined the parameters to be consistent with those for a contemporary transonic transport aircraft. He then began the detailed layout of the wing, fuselage, and horizontal tail. Peg Curtin and Ben Rider (also of Boeing) provided a representative, generic flow-through cowl and pylon design. Vassberg designed an initial wing with Anthony Jameson, using Jameson's SYN107 code (Ref 14). However, a requirement for the final wing design was that it be high performing with and without the nacelle-pylon group included. To accommodate this requirement, as well as to incorporate some additional features into the wing design, Vassberg made the necessary modifications. At this stage, the complete wing/body/nacelle/pylon/horizontal-tail geometry was defined by a discrete set of surface points taken from a structured CFD mesh system.

In order to surface the networks of discrete points, a utility within the Aerodynamic Geometry Panelling System (AGPS) (Ref 15) was used to perform a quintic fit through them. The complete fuselage was originally fit as one surface, without cut-outs at the wing or horizontal-tail intersections. Such cut-outs were subsequently introduced, although the definition of the fore-body remained rather coarsely defined. The wing was lofted from an aerofoil stack into four patches: splits were introduced at the planform break (to yield inboard and outboard segments) and at the leading- and trailing-edges (yielding upper and lower surfaces). These four patches were fit independently of each other. As a consequence, a small discontinuity in surface tangency was introduced along the entirety of the wing leading-edge. The horizontal-tail was defined by two aerofoil sections: one at the symmetry plane and one at the tip. Like the wing, it was split into upper and lower surfaces which were fit independently. The hinge-line of the horizontal-tail was defined as an unswept horizontal line.

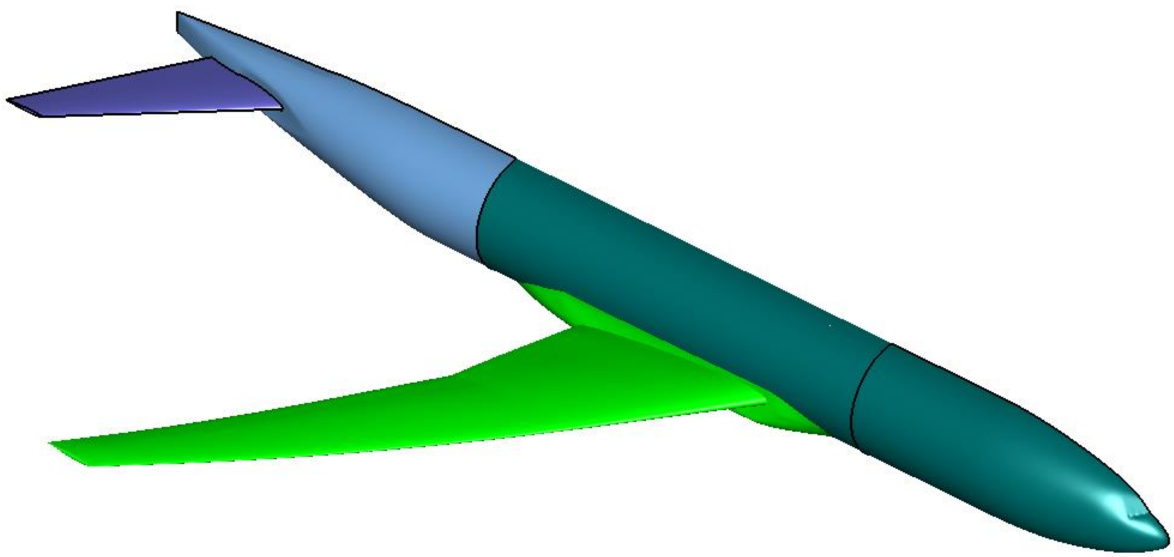


Figure 2. A NASA CRM Wing/Body/Horizontal-Tail Configuration used in DPW 4 and DPW 5

While much has been done to refine an expand on them since (see for example Ref 16), these surfaces, referred to as Version v03, were provided for use in DPW 4 and were subsequently re-used in DPW 5.

III. Geometry Models, As Supplied

The geometry models of the NASA CRM that were made available for DPW 4 and DPW 5 (i.e. v03) were supplied in IGES format. Access to the files was (and still is) provided via NASA-hosted websites (Refs 11 and 12), which loosely (Ref 8) refer to the geometry models as "CAD Models". In this paper, we examine the model of the Wing-Body-Tail iH+0 Configuration (as supplied in file `DPW4_wbt_ih+0_v03.igs.gz`) shown in Figure 2. (Note: the IGES files only contain data for the starboard side of the airframe). Although this does not include the pylon or nacelle components featured in the original NASA CRM design - and recently made available for use in DPW 6 (Ref 17) – this is the model that most researchers have used to date and, as will become apparent, much has been learned about its construction since it was released in November 2008.

IV. Geometry Pre-Processing Requirements

The following assumes that the geometry input required by the mesh generation process is a topologically watertight Boundary REPresentation (BREP) of the airframe in question, consisting of a series of suitably connected parametric surfaces. Provision of additional mesh generation requirements, including textural Mark-Up (see e.g. Ref 8), the imposition of a symmetry plane and definition of a far-field bounding box, is beyond the scope of the current paper.

The activities required to convert the data contained in the IGES file, as supplied, into a form of OML suitable for CFD mesh generation are outlined below, under the following broad headings:

Format Corrections: These are primarily required to address ambiguities in the supplied data and would not normally be expected to result in any tangible change in the OML. Some IGES "post-processors" (software that translates data supplied in IGES format into the desired target format - e.g. native MCAD or whatever is used by the mesh generation software) may deal with these ambiguities automatically. However, the details of how this is accomplished are not always clear to the user and, in extreme cases, may cause problems during mesh generation. More importantly, as will be shown, in the case of the v03 geometry models, most ambiguities in the supplied IGES data may be avoided simply by adopting a different approach to IGES "pre-processing" (translation of the geometric data from its original form into IGES).

Fundamental Modifications: These are required to accommodate fundamental errors in the supplied data, such as gaps or regions where the OML are not defined. If such gaps are larger than the tolerance(s) being used by the mesh generation software, it will not (normally!) be possible to generate a surface mesh. In the absence of further guidance, the decision as to how to proceed in these circumstances is, of necessity, left to the user. Unfortunately for a geometry model developed specifically to support CFD validation activities, regions of the model requiring fundamental modification, although small, exist. Associated corrections have been incorporated into the models that have been made available for DPW 6 (Ref 17).

In order to describe the needs for Formal Correction and Fundamental Modification, it is helpful first to unpack what is meant by a "topologically watertight Boundary REPresentation (BREP)".

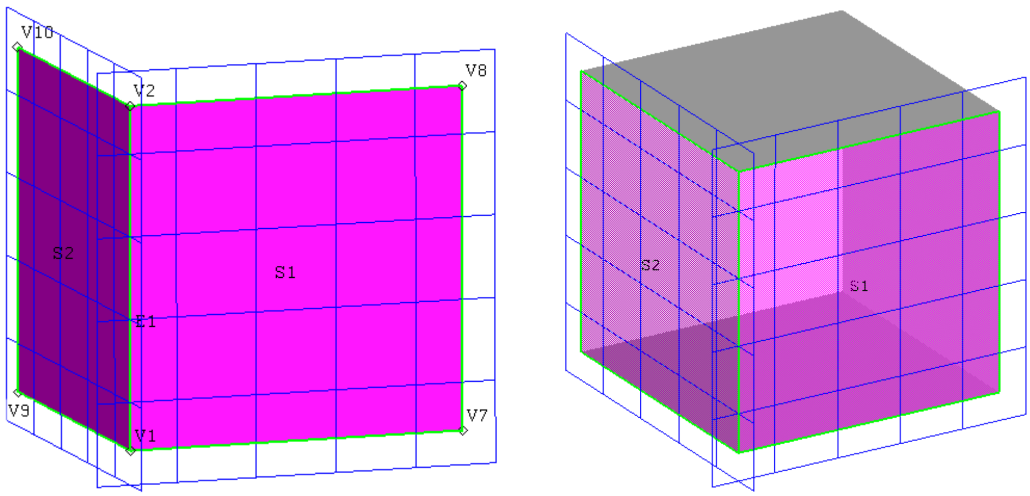
A. Desired Outcome

The prevalent way in which solids are currently modelled in engineering applications is via the judicious use of BREPS. These are formed almost exclusively by intersecting two-dimensionally parametric surface patches, as required; the resulting (trimmed) regions of each surface patch between the intersections forming a component of the BREP, as illustrated in Figure 3. This shows a small region of a BREP formed by two intersecting surface patches, S1 and S2. Figure 3a identifies the key underlying properties of both surface patches: their vertices (only the trimmed vertices are labelled), their edges, their underlying (two-dimensional) parameterisation (highlighted in blue) and the curve defining the intersection between them (C1). For simplicity, Figure 3b identifies the contributions made by these surface patches to the overall BREP of a cube. Note that, in order to maintain the integrity of the trimmed surface patch definitions, it is necessary to maintain the untrimmed portions of the underlying surface patches as part of the BREP model (in general, their removal would modify the shape of the trimmed patches).

The following features of Figure 3 are particularly noteworthy:

Each surface patch – trimmed or untrimmed – is bounded by a series of edges connecting vertices. These vertices must be connected in an order that allows the windward side of each surface patch to be identified correctly, meaning that each edge must be defined in a specific direction and connected in sequence. (Conventionally, the required direction is anti-clockwise when viewed from the outside.) The vertices shared by adjacent trimmed surface patches – i.e. those delineating the exposed ends of intersection curves – must therefore be connected in opposite directions when used to define the trimmed surface patches they bound.

While the underlying untrimmed surface patches are parametric, their intersections are not: in general, they are evaluated on a point-by-point basis, in each case the result only being accurate to a pre-defined tolerance. Consequently, intersection curves do not necessarily lie precisely on the trimmed surface patches they are considered to bound. Moreover, it follows that, while the edges bounding an untrimmed surface patch will follow a closed loop, those associated with a trimmed surface patch might not (vertices at the "intersecting" ends of two intersection curves may not be perfectly coincident).



(a) Underlying parametric surfaces **(b) Their contributions to a simple BREP**

Figure 3. Simplified illustration of the way in which parametric surfaces are used to form BREPs

Unfortunately, there is no known way of completely avoiding these "leaks" when using the form of BREP illustrated in Figure 3. Thus OML defined in this way will not, in general, be perfectly watertight. To build a measure of robustness against the inevitable leakage, contemporary mesh generation tools tend to require merely that the OML are topologically watertight – that is, that only the bounding curves of the trimmed surface patches need be watertight - and even then only to a permissible tolerance. (Any local leakage that may occur between adjacent surface patches is simply meshed over on the basis that the attendant effect on the local OML is very small indeed – usually appreciably smaller than the local surface mesh cells and well within manufacturing tolerances – and was not unambiguously defined in the first place.)

The latest published version of IGES (5.3, Ref 18, published over a decade before DPW 4) supports the form of BREP illustrated in Figure 3 directly, via what it terms Boundary (Type 141) and Bounded Surface (Type 143) Entities (although there is no explicit mechanism for defining the connectivity between trimmed surfaces – information that must therefore be implied from the bounding curve definitions). However, these types of entity were not used in the IGES files supplied for DPW 4 (which were generated using a pre-processor compliant with IGES 5.0).

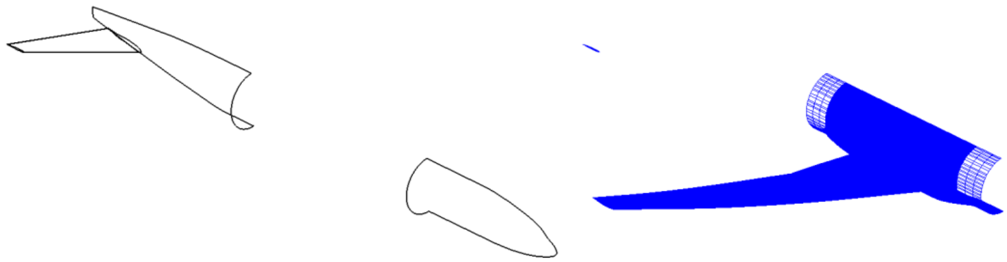
B. Format Corrections

A list of the IGES Entities contained in the supplied geometry model is presented in Table 1. Focussing, for the time being, on the surfaces contained in the model: there are 28 Rational B-Spline Surface (Type 128) Entities, of which 5 have been supplied with corresponding Trimmed (Parametric) Surface (Type 144) Entities.

Type	Description	Total
102	Composite curve	12
108	Plane	32
124	Transformation matrix	7
126	Rational B-spline curve	55
128	Rational B-spline surface	28
142	Curve on parametric surface	6
144	Trimmed (parametric) surface	5
314	Color Definition	4
406	Property	8
410	View	8

Table 1. List of IGES Entities contained in file `DPW4_wbt_ih+0_v03.igs`

These surfaces are presented in Figure 4: the trimmed surfaces are shown in Figure 4a; the remaining untrimmed surfaces in Figure 4b.



(a) Trimmed surfaces (bounding curves) **(b) Untrimmed surfaces (wireframe view)**
Figure 4 Surfaces contained in file `DPW4_wbt_ih+0_v03.igs`

Considering first the trimmed surfaces (Figure 4a): Pointers to curves defining their outer boundaries are intrinsic components of the definition of these Entities. These must be Curve On A Parametric Surface (Type 142) Entities, of which there are 6 in the supplied model). A crucial difference between the supplied Type 144 and 142 Entities and the Type 143 and 141 Entities described in Section IV.A above is that the latter include an edge sense flag. This allows the normal vector on each surface to be defined explicitly and both eases and de-risks the post-processing task of inferring surface connectivity (since the Type 141 boundaries may be shared by intersecting surface patches).

A factor that can cause unexpected effects during any subsequent mesh generation is the existence of very short bounding curve entities defining the boundary of a surface patch – these can lead to the local production of undesirably small surface mesh elements, for instance. Even though such entities are rarely introduced by design (i.e. with the explicit intention of the engineer developing the model), there are several reasons why such entities may be generated. These are almost exclusively a consequence of the ways in which geometric tolerancing has been applied – e.g. to ascertain whether points (or vertices) lie on edges (or surfaces), or whether edges lie on surfaces, etc.

Entity 261 provides an interesting example of the problems that can be encountered. This entity is the surface used to define the trailing-edge of the horizontal tailplane: at its intersection with the upper surface, its trimming curve at the tip of the tailplane originates approximately 0.05 inch (1.27mm) too far outboard – see Figure 5. The corresponding extent of the unintentionally exposed forward-facing portion of this surface is a more modest 0.004inch (0.1mm) normal to the trimming curve. (Note that both of these dimensions are quoted at the supplied model scale.) An elegant solution to this problem would simply be to move the whole trimming curve inboard (and thereby effectively remove the error).

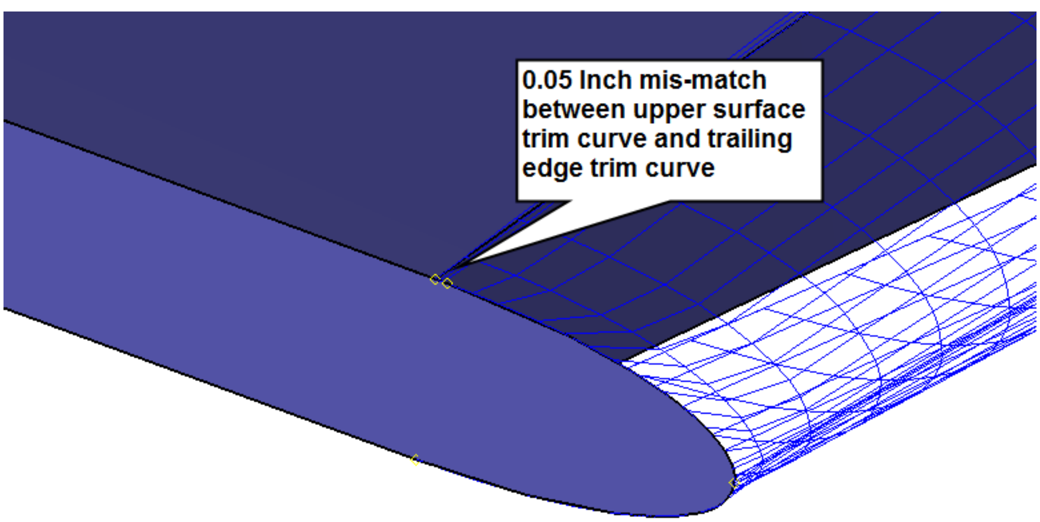
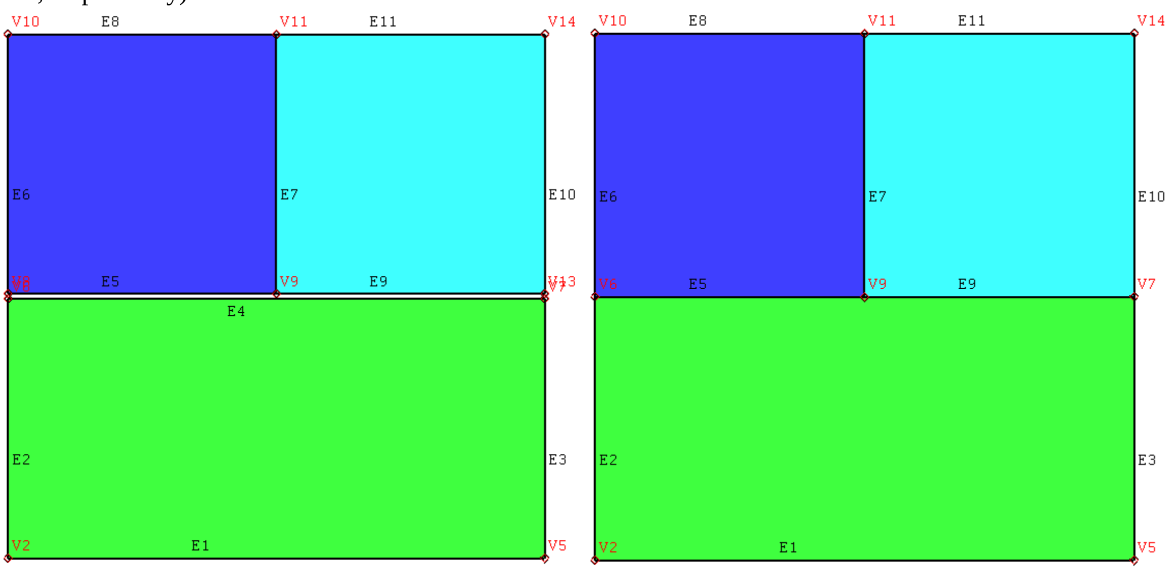


Figure 5. Close-up view on outboard end of horizontal tailplane trailing edge (Surface forming the curved wing-tip shown in wireframe)

There is no universal approach to the problems arising from the need to handle geometric tolerances – different geometry kernels (and mesh generators) behave in different ways. Moreover, IGES does not mandate any particular approach; consequently, no tolerancing information is transmitted explicitly in the supplied IGES file. (In this context, it is interesting to note that the minimum user-intended resolution or granularity of the model, quoted as 3.937*10-7inch (1*10-6mm) in the General Section of the file, is exceeded throughout: the gaps between adjacent surfaces are rarely within this tolerance anywhere in the model.)

The importance of addressing this feature of the supplied model, together with details of the corresponding actions (if any) required, will be dependent on the local context of its use, i.e. the behaviour of the IGES postprocessor and the response of the mesh generation software. Another action that may be required prior to the use of some mesh generators is the removal of any non-wetted (internal) surfaces, such as the inboard closure surface of the wing (Entitiy 279). In view of the dependency on local tooling, and of the range of potential options available, further discussion of these subjects is beyond the scope of the current paper.

In view of the potential variability associated with the handling of geometric modelling tolerances, it is good practice when generating geometric models for use with CFD to ensure that, where possible, the vertices of all surface patches are clearly identified on all of the bounding curves present at intersections. This is illustrated in Figure 6, which shows the pertinent features of a T shaped intersection between three surface patches: in Figure 6a, edge E4 (running along the top of the green surface patch) is unbroken; Figure 6b shows the preferred situation, in which this edge has been split and replaced by edges E5 and E9 (which are shared with the dark and light blue patches, respectively).



(a) Boundary curves not shared **(b) Boundary curves shared**

Figure 6. Surface connectivity at "T" junctions

The benefits of applying such corrections to the supplied model are likely to be more pronounced for the untrimmed surfaces shown in Figure 4b, than the Type 144 entities of Figure 4a. This is because the definition of Rational B Spline Surface Entities (Type 128) does not contain any boundary curve information. No bounding curve data for these entities is supplied in the model: it is implicit that the limiting iso-parametric curves be used. Thus, unless action is taken, there is a total dependency on the IGES post-processing software and/or the mesh generation tool to deduce the correct surface connectivity and define the edges in such a way as to avoid unintended features being generated in the resulting computational mesh.

C. Fundamental Modifications

While most – if not all – of the Formatting Corrections described above can usually be avoided by judicious use of IGES post-processing software, there is one Type 128 surface patch in the supplied model that can create problems: Entity 275. Illustrated together with its underlying parameterisation in Figure 7, this defines the region of the fuselage adjacent to the wing.

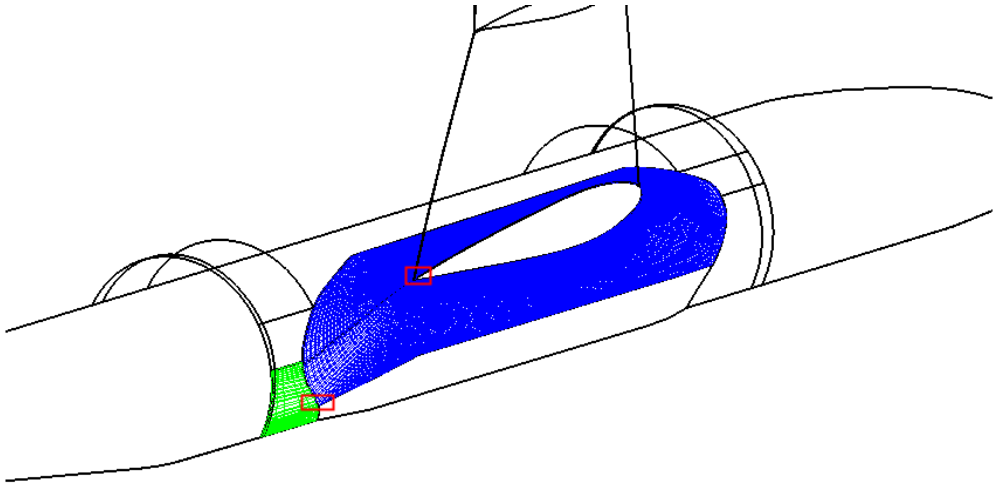
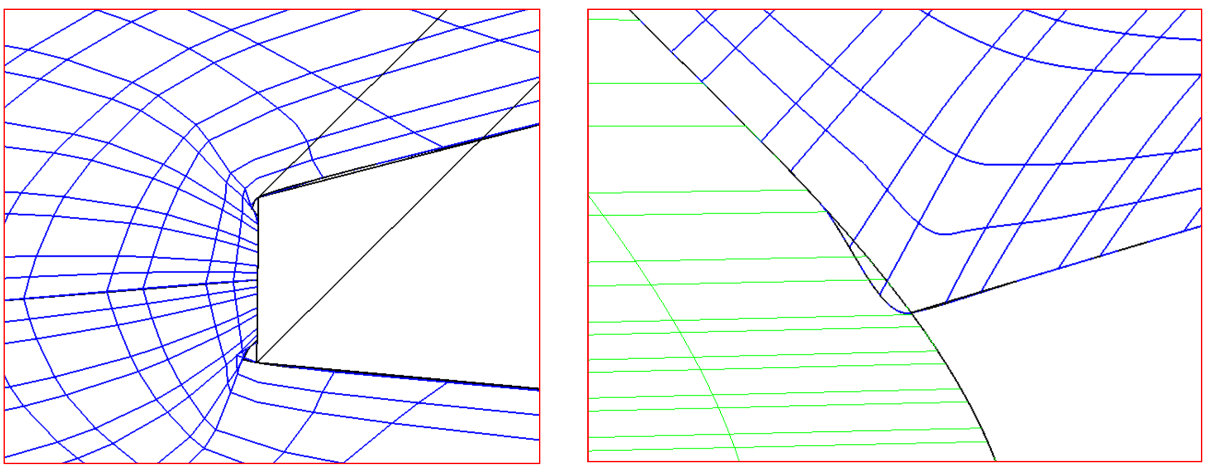


Figure 7. View on the wing body junction, highlighting surface patch Entity 275 (blue wireframe)

The principal problems associated with this surface patch are illustrated in Figure 8: Figure 8a shows that there are gaps in the side of the fuselage adjacent to the wing trailing edge. The maximum extent of the larger gap is approximately 0.064inch (1.63mm). Figure 8b illustrates that there is an overlap between this (untrimmed) surface and neighbouring (untrimmed) surface Entity 269. The maximum extent of the overlap is approximately 0.9inch (22.8mm). Untreated, both of these features of the supplied geometry model – gaps and overlap – would be expected to cause problems for surface mesh generation.



(a) View on trailing edge – fuselage junction **(b) view on lower aft fuselage**
Figure 8. Close-up views from Figure 7
(Entity 275: blue wireframe; Entity 269: green wireframe; untrimmed bounding curves: black)

The reasons for these problems occurring are straightforward: the surface boundary for surface patch Entity 275 is simply too complicated for its underlying (two-dimensional) parameterisation – which, from the Figures, is clearly both distorted and irregular. An elegant solution would be to split the patch into a number of smaller, topologically rectangular patches – although this would require particular care to be taken to ensure continuity in their profiles is maintained, especially at the newly-created intersections. The solution adopted in the IGES model provided for DPW 6 was to make some detailed modifications to the way in which the surface was constructed (control points were repositioned into a more regular, non-folded, arrangement) and ensuring that the surface was trimmed appropriately: the results of these modifications are illustrated in Figure 9.

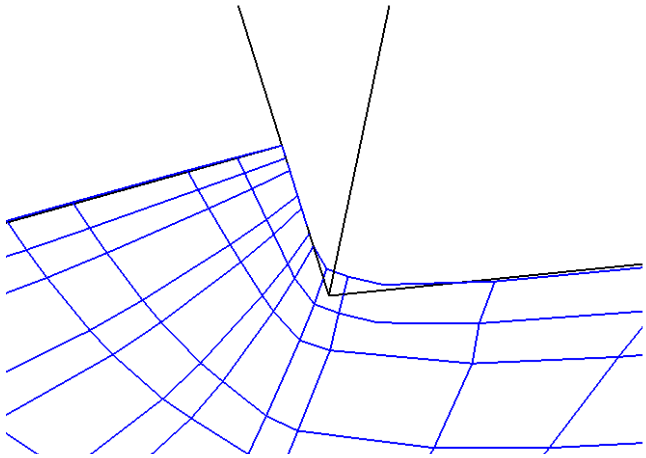


Figure 9. Close-up of the lower part of Figure 8(a), as supplied for use in DPW 6 (Updated, untrimmed version of Entity 275: blue wireframe; untrimmed wing bounding curves: black)

V. Additional Observations

Two further observations are offered concerning the supplied geometry model:

(1) The definition of the cockpit wind-shield shows evidence of rippling that would not occur in a practical design. This is illustrated in Figure 10a, which show that the entire forward portion of the fuselage has been represented using a single surface patch. The reason for the rippling is that the frames of the wind-shield are not locally coincident with iso-parametric lines in the underlying surface. A remedy would be to use a group of simpler surfaces that are intended to be trimmed (by their intersection with the windows. This is, essentially, the solution that has been adopted for use in DPW 6 (shown in Figure 10b).

(2) For an item that is essentially cylindrical and circular in cross section, the number of splines defining the central portion of the fuselage appears excessive – see Figure 11. Moreover, the underlying parameterisation is neither uniform (a residual influence of the block-structured surface mesh origins of the OML) nor consistent with the (adequate but appreciably coarser) level of definition in the adjacent surfaces (forward and aft) – see Figure 4b. The cylindrical nature of this region of the OML reduces the likelihood of this unusual form of underlying parameterisation leading to problems or unexpected results being encountered in mesh generation. However, the same could not be said if similar features were present in surfaces possessing double curvature – small, localised undulations similar to those evident in Figure 10a might result, for instance.

VI. Closing Remarks

The material presented above raises some interesting general questions concerning not only the format, but also the form in which airframe OML should be defined for use with CFD.

While IGES may, in principle, provide a sufficient format for capturing and conveying the type of airframe topology embodied by the NASA CRM (which, in the wider scheme of things, is relatively straightforward), it does not support the broader aspirations of the virtual business enterprise (Ref 19). As a result, its development and use are in decline: no updates to the standard have been published in virtually two decades; several components of the latest Version (5.3) have not been fully tested; others are not widely supported. Significant upgrades in the current IGES pre- and post-processing capabilities of commercial software packages are unlikely. The contemporary mechanism for supporting the wider business requirement is via STEP (Ref 20). However, this standard, including those Application Protocols most pertinent to CFD, is still under active development; its full scope has not yet been realised. Hence, while adoption of STEP is becoming increasingly widespread, its use is far from universal (even in the CFD community) – as may be judged from the variety of formats in which the NASA CRM geometry model has been supplied for DPW 6 (IGES and STEP, together with a number of native MCAD formats, Ref 17).

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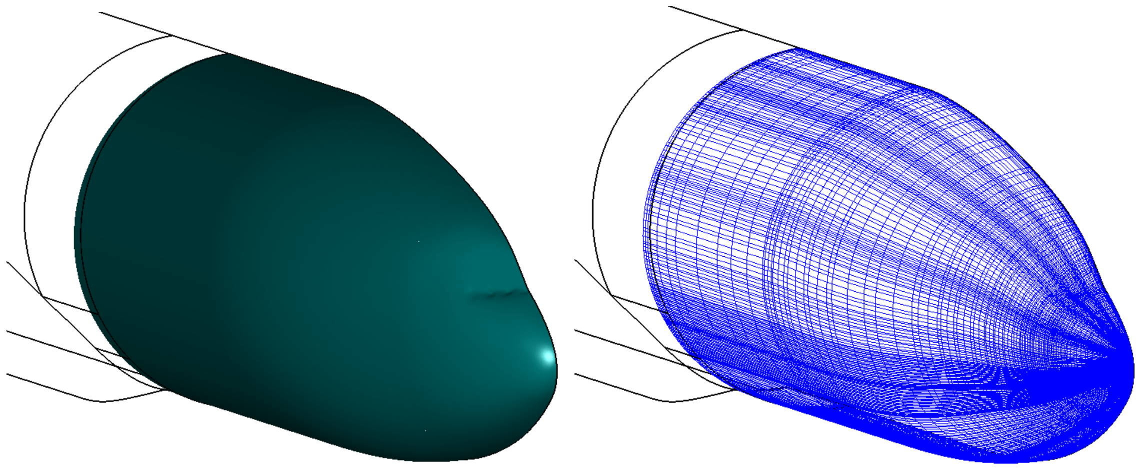
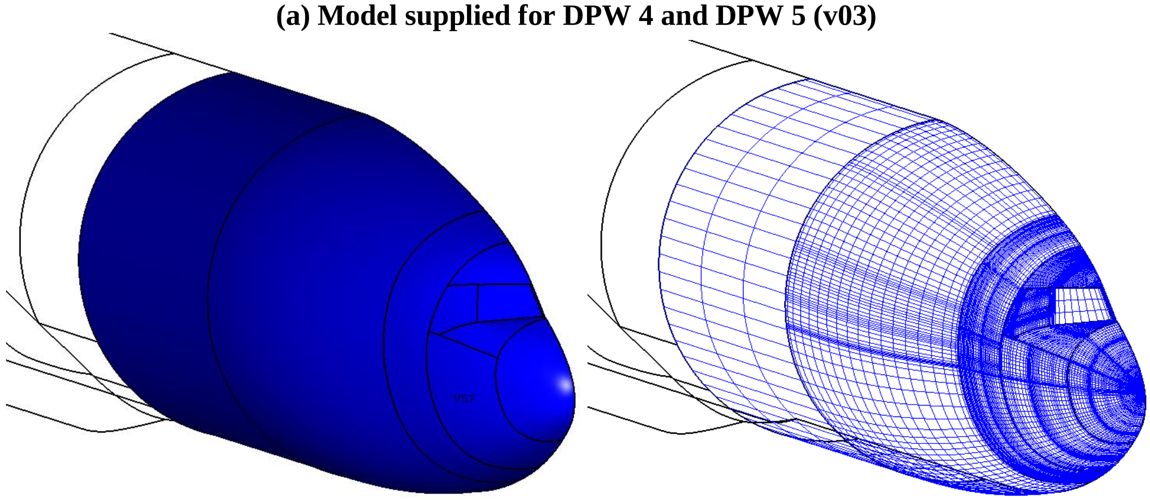


(a) Model supplied for DPW 4 and DPW 5 (v03)



(b) Model supplied for DPW 6 (v09)

Figure 10. Cockpit wind-shield detailing

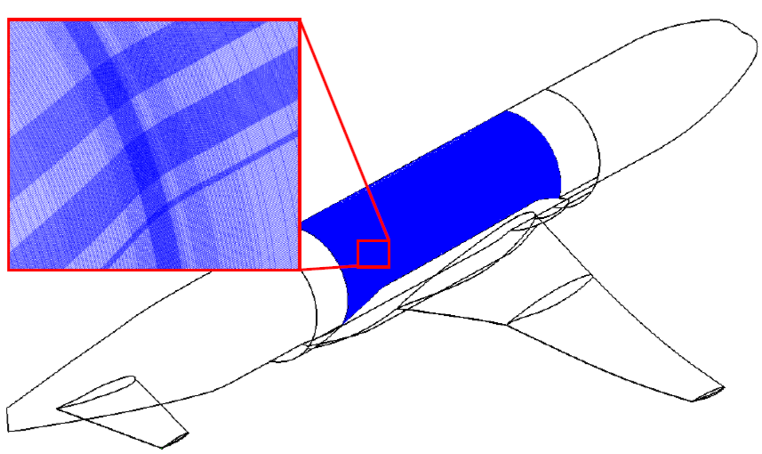


Figure 11 Example of the irregular underlying surface parameterisation of the fuselage

As originally supplied, the NASA CRM geometry models were intended to support CFD validation: they were not primarily conceived as providing a platform for evaluating subsequent refinements to their aerodynamic design, or assessing the effects of aero-elasticity, for instance. This distinction is important as the way in which OML are parameterised (including the manner in which the OML are discretised into surface patches as well as the way in which underlying parameterisation of each patch is defined) will determine the ease with which it is possible to manipulate them which, in turn, will ultimately constrain the performance gains achievable. Entity 275 (Figure 7) provides a case in point: the most appropriate means of modifying its profile without exacerbating the problems described in Section IV.C, above, or introducing local irregularities are not immediately apparent. Potential difficultiess that may be encountered in subsequent mesh generation also need to be accommodated, as attested by the motivations behind a recent update to the underlying parameterisation of the main wing tip (Ref 16). The simultaneous requirements for direct access to the underlying surface parameterisations and precise control over the way in which geometric tolerancing is implemented are two of the principal reasons why a reliance on bespoke Pre-CAD software for generating airframe OML is so prevalent in the aerospace industry.

The choices to be made when parameterising OML are complex and far-reaching. For instance, at first sight, decisions regarding the layout of surface patches may seem analogous to the challenges of generating the topology for a block-structured mesh. However, in this case, the underlying parametric directions of adjacent surface patches, while being two-dimensional, need not be aligned. Moreover, a degree of overlap between adjacent patches (removed by trimming the patches at their intersection) may be desirable, or in certain locations, even necessary. Aside from anything else, these freedoms (wrt alignment and overlap) can both provide convenient mechanisms for accommodating the disparate forms of component - aerofoil, wings; nose, belly fairing, fuselage - parameterisation that will be almost inevitably required to build a complete airframe configuration. On the other hand, BREPs based on the forms of topology illustrated in Figure 3 can be "stiff", i.e. difficult to modify without introducing localised surface irregularities (discontinuous changes in curvature at the patch boundaries, for instance). A variety of approaches are being developed to address these challenges – local spline refinement schemes, sub-division surfaces and implicit schemes using level sets, for instance – although these are not yet supported by STEP. The above presumes that manipulations are applied directly to the OML: this is not always the case. Indeed the vogue in the CFD community has, for many years, been to deform the mesh rather than the OML. (Although it is recognised that this is not an ideal solution, since mesh adaptation requires access to the underlying OML, for instance. There are also challenges associated with subsequent transfer of the – deformed - surface mesh back to MCAD.) The interested reader is referred to Ref 8 for a wider introduction to these matters.

The value of having access to a geometry model, together with supporting aerodynamic performance data, like the NASA CRM should not be under-estimated. Since its original release for use in the AIAA Drag Prediction Workshops, the NASA CRM has played an important role in the assessment and development of various CFD-related techniques and technologies. Its valued use continues – as the basis for test cases used in various AIAA workshops (e.g. Refs 13, 17 and 21) and the AIAA Aerodynamic Design Optimisation Discussion Group (Ref 22), for instance is essentially cylindrical and circular in cross section, the number of splines defining the central portion of the fuselage appears excessive – see Figure 11. Moreover, the underlying parameterisation is neither uniform (a residual influence of the block-structured surface mesh origins of the OML) nor consistent with the (adequate but appreciably coarser) level of definition in the adjacent surfaces (forward and aft) – see Figure 4b. The cylindrical nature of this region of the OML reduces the likelihood of this unusual form of underlying parameterisation leading to problems or unexpected results being encountered in mesh generation. However, the same could not be said if similar features were present in surfaces possessing double curvature – small, localised undulations similar to those evident in Figure 10a might result, for instance.

References

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