TOWARDS THE VIRTUAL PRODUCT IN AIRCRAFT DESIGN?

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Abstract. The Virtual Product in the context of this paper concerns the design of the physical properties and the functions of the airframe. After the definition of the Virtual Product, the two driving factors for it, the present-day business climate of aircraft industry, and the weakening of Cayley´s design paradigm are discussed. The enabling factors of the Virtual Product, high-performance computation and information technologies in general, as well as modern numerical simulation and optimisation methods, are considered. Finally the challenges, which the Virtual Product poses, are discussed: mathematical/numerical product models, flow-physics and structure-physics models, implementation and acceptance, and staff qualification and education.

Key words: aircraft design, Cayley´s design paradigm, high-performance computation, information technologies, multidisciplinary simulation and optimisation methods, product models, flow-physics models, structure-physics models

1 INTRODUCTION

Numerical Fluid Mechanics has reached a high level of maturity[1]. In aircraft design, especially in aerodynamic shape definition, Numerical Aerodynamics is now an established tool. This is due to large algorithmic advances, advances in computer science, but also to cheap computer power, despite some remaining bottlenecks like grid generation and flow-physics modelling, i. e. modelling of laminar-turbulent transition, turbulence and separation. Of course, the wind tunnel will keep its major role as verification and data-set generation means for many years to come. New tunnels, like the European Transonic Wind Tunnel (ETW), offer very accurate and repeatable aerodynamic simulations in realistic Mach number and Reynolds number regimes. This capability, however, is not yet matched with appropriate aerodynamic design tools, due especially to the lack of sufficiently accurate and robust flow-physics models.

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Linear aerodynamic methods in structural dynamics begin now to give way to non-linear methods, which is overdue in the transonic regime. In general, multidisciplinary numerical simulation and also optimisation is evolving.

All this reflects the second wave of "mathematisation" of so far more or less empirical disciplines, which can be observed since about ten years, after high-performance computer architectures became available. The first wave, especially concerning aerodynamics and fluid mechanics, happened about one hundred years ago, and is connected mainly to the name of Ludwig Prandtl.

The second wave of mathematisation appears in a time with profound changes in the aerospace business, and therefore it must be seen, how use can be made of it. The present paper looks at the new challenges in aerospace industry. The Virtual Product concept is put forward and discussed in general terms. Emphasis lies on the design problems of the airframe (work on numerical multidisciplinary simulation and optimisation methods in this regard was proposed, and is conducted, for instance, in Germany[2,3]). Of course the concept can be extended to any design problem. Research and development work at many places is testimony of that.

Provided that an adequate effort is spent, the basic version of the Virtual Product could be available in the near future. The full functionality could be reached in about five years, and the finally necessary accuracy in about ten years. Industry would benefit strongly from the begin, because this approach will reduce effectively time and cost to market for its products. In addition, it is indispensable to overcome the design problems of future, even higher than now integrated aircraft.

2 WHAT IS THE VIRTUAL PRODUCT?

In the frame of this paper the definition of the Virtual Product is the following:

"The Virtual Product (VP) is a high-fidelity mathematical/numerical representation of the physical properties and the functions of a product".

Of course any representation of the properties and the functions of a product could be called a Virtual Product. Here the emphasis lies on "high fidelity". "Product" in the present context is a product in the definition phase, but also in any other product phase (see the next chapter). It can also be the product as a whole or a component of it. It can be a new development, a derivative, or an upgrade of a product.

What can the Virtual Product effect in aircraft design? This is shown in Fig. 1. Today the "knowledge" about the product in the product-definition phase is characterised partly by a rather low representation fidelity. This is increased during the development phase, when extensive ground-facility testing is made to improve the design, to verify it and to obtain the product data base (of course the picture may be different for the different involved disciplines). Flight testing is performed at the end for system identification purposes, which gives then a consolidated data base of the product.

The Virtual Product aims for a very high representation fidelity already in the product definition phase. Ground-facility testing, as well as flight testing, would be more or less done only for verification purposes. This, however, would be a complete departure from the present "classical" approach. The potential benefits of the high fidelity representation of the physical properties and the functions of the product, i. e. the Virtual Product, early in the definition phase, but also in the other product phases, are obvious:

- improved feasibility statements,
- avoidance of over-specifications,
- improved definition of sub-systems,
- more effective integration of suppliers,
- more effective identification of sensitivities,
- earlier problem identification,
- reduction of design margins,
- better control of life-cycle cost,
- more reliable programme decision criteria,
- effective demonstrations for the customer,
- support of the certification process,

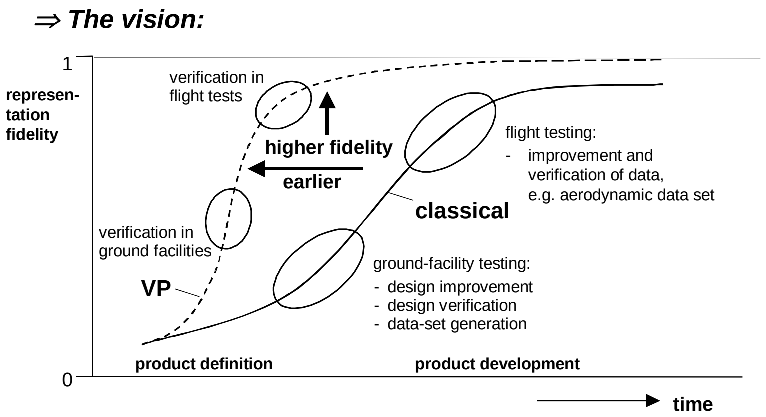

Fig.1 Schematic description of the effect of the Virtual Product in aircraft design

and hence reduction of:

- the number of design cycles,
- development risks,
- flight tests,
- cost and time to market,
- possible later repair solutions.

The important prerequisites of the Virtual Product, high-performance computation and communication technologies, as well as numerical process technologies, are shown in Fig. 2. They are on the one hand high-performance computation systems, including information and communication technologies in general. On the other hand they are very advanced process technologies, which are basically multidisciplinary numerical simulation and optimisation methods. They build on mathematical/numerical product models, together with appropriate flow-physics and structure-physics models. All these are discussed in some detail as enabling factors in Chapter 4, and as the big challenges, which they pose for research and development work, in Chapter 5.

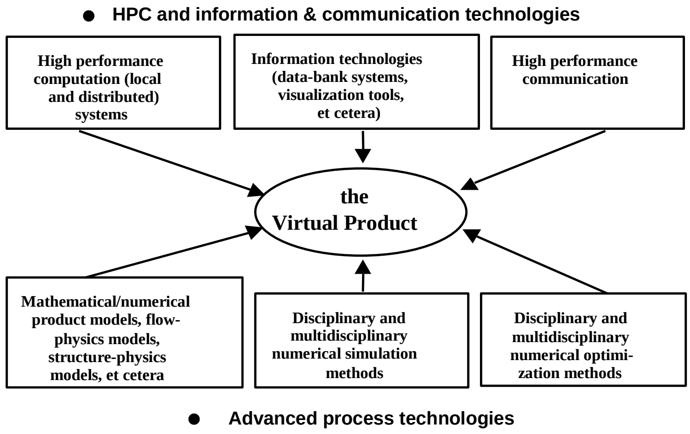

Fig. 2 Prerequisites of the Virtual Product

3 WHY THE VIRTUAL PRODUCT: TWO DRIVING FACTORS

3.1 Business climate

One of the driving factors of the Virtual Product is the present business climate. Aircraft manufacturing has undergone strong changes in the last decade. The paradigm change in the product philosophy from the "technology driven" to the "market driven" design is even older. Now the "privatisation" of the aircraft industry, economical – and ecological – pressures, the need to finance new products over the capital markets, the world-wide competition scenario – globalisation – with the USA, the Far East, and in future certainly again Russia, and also the internal European competition, are driving the business[4]. Of course, the scenarios are somewhat different in the military and the civil aircraft branches.

However, the particularities of the business of aircraft industry have not changed. There are still large technology development efforts with big risks, even before the definition phase for a new product, Fig. 3. Especially with military aircraft the time intervals between projects are becoming larger and larger, and hence also the technology jumps. The product definition and development phases are long, except for derivatives of, for example, already existing

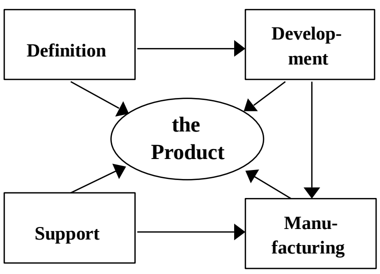

Fig.3 Schematic of product phases

transport aircraft. Small series with large cost per unit entail a restricted correction potential of possible design mistakes. In addition usually a large and long capital tie-up happens, with a very late net output (break-even point). Long product life cycles, however, lead to stable support business.

All this leads to the strong necessity of risk minimisation – "first time right" – and a definitive reduction of cost and time to market in order to maintain and improve the competitive edge, and the profitability of the business.

3.2 Weakening of Cayley´s design paradigm

The other driving factor is the weakening of Cayley´s design paradigm. Sir George Cayley (1773-1857) was an early British aviation pioneer. Cayley´s design paradigm, the name is introduced here in order to pin-point one of the driving factors of the Virtual Product, reads (not in his own words):

- Assign functions plainly to corresponding subsystems, e. g.

- wing	⇔	provision of lift,
- propulsion unit	⇔	provision of thrust,
- tail unit	⇔	pitch/yaw trim, stabilisation and control,
- fuselage	⇔	payload accommodation,
- et cetera.		

- Have the different functions and the corresponding subsystems only weakly and linearly coupled,
- then you can treat and optimise each function and subsystem more or less independently of the others,
- and nevertheless treat and optimise in this way the whole aircraft, which integrates all functions and subsystems.

This differentiation has been proven to be very effective (ideally it should hold for every product). However, the quest for more performance and efficiency, the opening of new flight-speed domains et cetera, has led over the years to higher and higher integrated functions and sub-systems. Of course, this is different for military and civil aircraft, and does in each case not necessarily encompass all major functions and sub-systems.

In the context of the present considerations it is interesting and important to note, that a similar differentiation has taken place also of the engineering disciplines, which are involved in the development of an aircraft. This is natural, and was and is indeed also a strong technological driving factor. This differentiation of the engineering disciplines, however, had also adverse effects. It led, for instance, to the presently strongly established sequential and iterative design cycles. It further led in some cases to autonomy drives of disciplines by duplicating – under the euphemism "adaptation" – skills and tools of other disciplines, which then often did not participate in the sub-sequential developments of the mother disciplines.

In view of these developments, the meaning of Cayley´s design paradigm is expanded to cover also the disciplines, i. e. both the differentiation of functions/sub-systems (first aspect), and of disciplines (second aspect).

The significant observation is now, that Cayley´s design paradigm is, as already indicated, persistently weakening in modern aircraft design. Some examples for this weakening are:

- Aeroservoelastics of, especially very large, aircraft: weakening of first and second aspect.
- Transport aircraft with high/ultra-high by-pass engines: weakening of first and second aspect.
- High-lift systems: weakening of second aspect.
- Unstable flying aircraft, today fighter aircraft, in future also transport aircraft: weakening of first and second aspect.
- Airbreathing hypersonic aircraft (very highly coupled lift/propulsion system with pre-compression by elastic forebody): weakening of first and second aspect.

In general it appears, that a strong and non-linear coupling of functions/sub-systems asks also for a strong discipline coupling. But there are also cases, where a strong disciplines coupling is mandatory, even if functions/sub-systems obey Cayley´s design paradigm.

The treatment of these design problems in the classical way is partly possible, but often it leads to increasingly large time and cost increments. Design risks can become large, and, especially with very strong functions/sub-systems couplings, they can become untenable.

The discussion shows, that the weakening of Cayley´s design paradigm, in both aspects, asks for new approaches, both in view of the “first time right” demand of present and near-term aircraft developments, and of future, technologically more demanding aircraft designs, with still higher integrated functions and sub-systems than now. These are, for instance, uninhabitated fighter aircraft, and unstable flying transport aircraft, as well as transport aircraft with unconventional configurations, hydrogen-fueled transport aircraft, et cetera. More in the future are hypersonic air planes, especially airbreathing aerospace planes, for both military and space-transportation purposes.

The question is, whether and how the Virtual Product can be a major element of a post-Cayley design paradigm, regarding both aspects of it.

4 THE VIRTUAL PRODUCT: TWO ENABLING FACTORS

4.1 High-performance computation and information technologies in general

One, probably the most important of the enabling factors of the Virtual Product is high-performance computation, which becomes available in future also for industry. The often articulated argument against high-performance computation in industry – not affordable – is not a real argument. The problem is the trade-off between design cost and risks, i. e. the benefit for the business, and, in this case, the cost of the Virtual Product approach including the computer cost.

It also does not help to look only at present computer cost. One has to look at its present gradient in time. Due to the persistent growth of chip performance (about a factor of ten every five years since now many years, Fig. 4), the picture changes fast in favour of high-performance computation. With fixed performance, the cost goes down, and with fixed cost, the performance goes up.

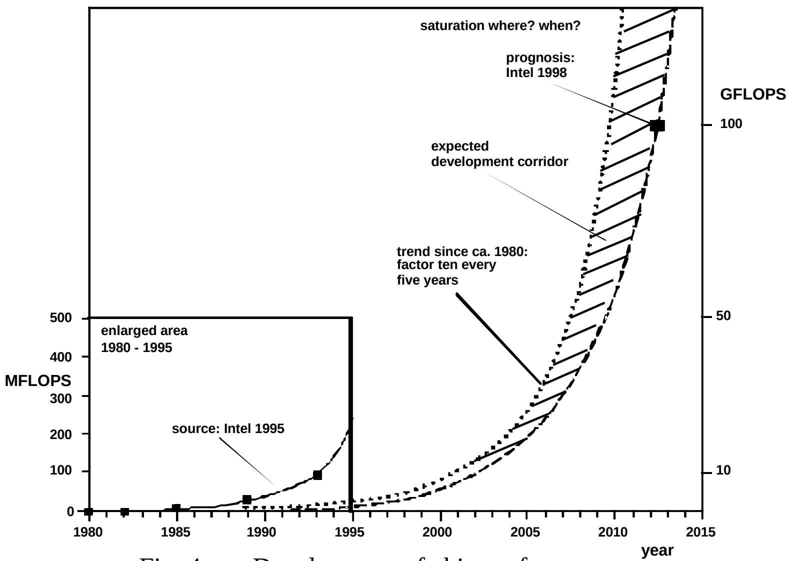

Fig. 4 Development of chip performance

Of course, the Virtual Product will demand more than Teraflops performance. This will be no problem. Imagine only what the Intel prognosis of 100 Gigaflops per chip in about ten years from now implies. The kind of computer architecture, which finally will be used, Fig. 5, also the possible use of massively distributed systems, of course is mainly a problem of algorithm design.

The other elements from information technology, Fig 2, are presently also growing at a fast pace. The strong improvements in software architectures like adapted data structures, object-oriented programming languages (e. g. C^{++}), parallelisation of codes, communication libraries, and so on, have strongly promoted industrial applications (data handling, reduction of turn-around times). Large advances are predicted for store technologies. Visualisation tools, which will be important for the Virtual Product, too, are driven strongly by applications outside of the aerospace sector. The same is true for high-performance communication. Not forgotten should be the fact, that high-performance computation and information technologies since long are conquering aerospace product technologies at increasing pace, too.

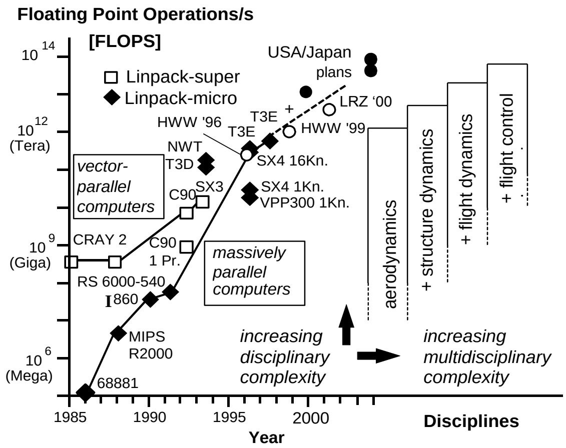

Fig. 5 Development of computer performance and its effect on process technologies in aircraft design

4.2 Numerical simulation and optimisation methods

The other enabling factor are the numerical simulation and optimisation methods of aerodynamics and structure dynamics. Presently the driving element is Numerical Aerodynamics. Large algorithmic advances, combined with extensive validation work, have led to fast and robust solution schemes. This also regards grid generation, which, as it looks now, will soon have reached the necessary maturity for industrial applications, both in numerical aerodynamics and numerical structure dynamics. New optimisation algorithms for aerodynamic shape finding[5], and also for numerical structure optimisation[6], are evolving. Large advances are presently made in the development of multidisciplinary numerical simulation and optimisation methods[7].

5 THE CHALLENGES

5.1 Mathematical/numerical product models

Underlying the Virtual Product are mathematical/numerical product models. The challenges to develop these product models are partly very large. They concern research and development efforts at universities, research establishments as well as industry. However, in any case efforts must be concerted efforts, because the problem definition for the necessary research and development work must put the industrial needs into proper perspective.

The general mathematical/numerical product (or system) modelling certainly will set up on existing models, to the degree as they are suitable. Otherwise new models must be developed, which have to take fully into account the need for adequate product definition and verification processes with increased cost efficiency.

This leads to the organisational structure of the involved disciplines of industry. On the one hand one has to ask to what degree their previous identities should be left intact in order not to weaken their capabilities. On the other hand one has to overcome their "historical" boundaries in order to gain the needed multiple interfaces, which are typical for concurrent engineering, which is in the background of the Virtual Product approach.

Sub-systems have to be treated, too, if they are strongly and non-linearly coupled to the system. Otherwise they can be represented by input/output models. The problem is how to handle their usually parallel development up to the final qualification, which can be, at least initially, as divergent as the development of the whole product.

Technical research and development work at universities, research establishments, and industry is necessary and underway on

- weak and strong coupling ansatzes between system/sub-systems and numerical solution domains in general,
- treatment of moving and deforming (aerodynamic) surfaces,
- structure dynamics in the time domain,
- aerodynamics/structure dynamics/flight dynamics/ flight control coupling,
- aerodynamic/thermal/mechanical coupling,
- model reduction for dynamic systems,
- et cetera.

5.2 Flow-physics and structure-physics models

Despite great algorithmic advances, Numerical Aerodynamics will not realise its potential as long as flow-physics modelling, i. e. modelling of laminar-turbulent transition, turbulence and separation in flows past real-life surfaces (with roughness, steps, et cetera), for both steady and unsteady flows, is not definitely improved. Like structure-physics modelling, it is and will remain, a severe bottleneck. However, the Virtual Product can initially be developed with weak flow-physics models. In view of the problems of flow-physics modelling, however, the latter must be attacked early with a pragmatic and perspective-oriented strategy. Present efforts are by far not large enough. Large-eddy simulation for high Reynolds number turbulent flow past whole aircraft configurations will not be feasible for many years to come, hence statistical turbulence modelling will have to remain the focal point.

If flow-physics models are not definitely improved, design problems like flutter, buffeting, stall, control-surface efficiency (especially for unstable flying aircraft), fast transient manoeuvre flow, et cetera will not find the adequate treatment, which is needed in design work. This does not only hold for the Virtual Product, but already for Numerical Aerodynamics for rigid configurations, and is also needed in view, for instance, of the ETW usage.

Structure-physics modelling poses other very large challenges. The present approach to assemble and test the airframe in ground facilities in order to gain its static and dynamic structural data sets with the needed high accuracy, is exactly was has to be overcome (Fig. 1). It is too late, the information is needed much earlier. The present approach has grown over many decades. It is necessary, because the Finite-Element (product) models and methods in use today do not permit to describe joints of all kind (which entail non-linearities and damping), general non-linear behaviour, and post-buckling. Hence the early in the design process needed data cannot be achieved with the necessary accuracy.

The challenges to change this approach are very large, too. Joint modelling, for instance, with the large scale discrepancies between a rivet, and the whole airframe, poses a problem similar to the turbulence problem, where also very different characteristic lengths appear.

Structure-physics modelling in this sense must also be attacked with a pragmatic and perspective-oriented strategy. The objectives of the Virtual Product, Chapter 2, can only be met with strong improvements of structure-physics models. Anyway the problems in aircraft design, if they are treated in the classical way, like static and dynamic aeroservoelasticity, notch-filter design, et cetera, will only get the adequate treatment with the help of high-performance computing, if the modelling issues are improved.

5.3 Implementation and acceptance

Implementation and acceptance of the Virtual Product approach both in research and industry need probably as large efforts as the development of the Virtual Product itself. Industry and research today still are organised and work discipline-oriented, in accordance especially with the second aspect of Cayley´s design paradigm. The problem can also be seen from another perspective. The often discussed and heralded Concurrent Engineering is indeed exactly, as already mentioned, what the Virtual Product demands. The question is, where are the problems, and who is to be addressed?

The high-fidelity representation of the physical properties and the functions of a product, for which the Virtual Product aims, will be achieved with new process technologies. That will meet at least in industry, as experience in many fields shows, acceptance problems on several organisation levels. The Virtual Product entails also system engineering and process changes (indeed, it aims for them), and hence organisation changes. Finally, and this must not be forgotten, it will introduce risks, as any new approach does, and the cost for its implementation must be recovered in due time.

Addressed is to be industry, which has to adopt fully the concept of the Virtual Product, whose driving factors were discussed in Chapter 3, further the research establishments and universities, and finally also the certification agencies, who must accept and approve the new approach. All organisation levels, from the management level down to the staff level are concerned. Psychological factors must be regarded. Incentives must be given. In industry they are cost and risk reduction in product design for management, and job security for the staff. In research they are the big scientific challenges of the Virtual Product in engineering sciences, in applied mathematics and in computer science, which will lead to very interesting results, and also will have positive effects in funding acquisition.

5.4 Staff qualification and education

The Virtual Product as a mathematical /numerical representation of the physical properties and the functions of a product is a tool. Tools are only as good as the people, who wield them. Innovative product design is first of all a matter of imagination, knowledge and creativity of persons. However, it can be dramatically enhanced with superior tools.

Given the very high complexity and integrativity of the Virtual Product and the (new) processes and organisations, in which it is to be applied, it is one of the greatest challenges for industry to build the staff with adequate qualification. Without that the Virtual Product will not unfold its potential, it even can become counter-productive. However, this holds for every process innovation, and therefore it is not a new problem.

On the one hand more persons of the staff will have to know more about the product and its sub-systems than now. On the other hand the use of high-fidelity multidisciplinary simulation and optimisation methods demands very broad knowledge of phenomena, mathematical/numerical models, and the methods themselves.

An extended education is necessary of available staff, and at the universities about

- process technologies:
  - disciplinary and multidisciplinary
    -- model building,
    -- discrete numerical methods,
  - information and communication technologies,
- product technologies,
- system technologies.

A problem will be university education, because the basic disciplines cannot be neglected. Hence it is the question how to shape university education without unnecessary and unwanted prolongation of it.

6 CONCLUSION AND OUTLOOK

The potential of the Virtual Product in aircraft design is large and needs to be exploited. The two driving factors are the present business climate, and the weakening of Cayley´s design paradigm. The central element of the Virtual Product is high-fidelity multidisciplinary numerical simulation and optimisation, which is becoming feasible because of the two enabling factors, the advances in high-performance computation and information technologies in general, as well as in numerical simulation and optimisation methods. Substantial research and development work is necessary for its realisation. Implementation and acceptance issues in industry and research must not be underestimated. For industry the Virtual Product is one of the few approaches with a large potential to reduce design risks, and time and cost to market. In addition it is indispensable to overcome the design challenges of even higher than now integrated future aircraft.

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