AC 2011-2659: ADVANCED CONCEPT DEVELOPMENT OF A HYDROGEN SUPERSONIC AIRLINER: SECOND ITERATION

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abstract

Developing advanced concepts offers several learning opportunities for undergraduates. Past work at 3 levels of undergraduate experiences laid out the changes that have occurred in global demographics and economics, and showed why a supersonic airliner architecture based on liquid hydrogen fuel presents unique opportunities in the near term. This paper discusses experience with a second iteration of concept development. Here a paper published by a previous undergraduate team was presented to undergraduate students taking engineering courses, along with a simple conceptual design spreadsheet. The students were asked to develop more refined aerodynamic and aeroacoustic predictions, re-examine the assumptions and procedures used before, and thus reduce uncertainties. They were also afforded considerable leeway to innovate, but at a deeper technical level. In a junior/senior course in high speed aerodynamics, student pairs studied the prediction of wave drag and compressible boundary layer drag, relating classical theory to detailed procedures using modern computer-aided design and conducting validations against linear theory. Results deal with the learning techniques that students used in each case, the experience of their use of cross-disciplinary, in-depth learning resources, and their adaptation to the idea of participating in advanced concept development which requires imagination and innovation, in courses where depth is demanded. The notion of a Figure of Merit is used again to focus thinking on assessing, improving and validating concepts.

introduction

At the 2010 Annual Conference [1], we presented the experience from 3 levels of students pursuing the idea that supersonic airliners fuelled with liquid hydrogen are viable in the near future. The technical and business case for hydrogen-powered supersonic airliners was re-examined as an exercise in multidisciplinary concept innovation by undergraduates at different levels. A progression of exercises was used. A conceptual design exercise in a freshman introduction course was expanded to modify a conventional hydrocarbon fuelled airliner concept to one using hydrogen fuel, quantifying the economic opportunities in the Carbon Market. Sophomores in research Special Problems were tasked with extending the freshman experience to supersonic airliners, as part of a team including senior students. These students explored radical concepts for such airliners. An upper level aerodynamics course was used to develop technical figures of merit for supersonic hydrogen airliners from basic aerodynamics knowledge. The process identified numerous gaps in the comprehension of the students from their courses. The integration challenge of this project enabled iterative refinement of their understanding. The concepts and analysis approaches taught at each level are seen to have become useful only when subjected to integrated use through several iterations. The paper also demonstrated a process to show how some certainty can be achieved in developing an ambitious advanced concept through the notion of a "figure of merit".

A multi-level process was laid out, to explore a high-risk, realistic concept using undergraduate participants. Vertical and horizontal knowledge integration aspects were explored, with differing levels of success and difficulty. A simple conceptual design procedure was used at the freshman level to permit students to explore advanced aircraft concepts and see what was needed to make the design close. This process was then used as the starting point to develop configurations in undergraduate research projects and an upper division aerodynamics course, where radical configurations on the one hand, and detailed technical calculations and optimization on the other, were performed.

The conclusions on the LH2 supersonic transport were very encouraging. As the cost of hydrocarbon fuel rises and the cost of hydrogen production comes down, LH2 becomes an ever more attractive option. As planned there, the concept exploration results from last year have become the starting point for this year's course assignments. The gaps in learning seen last year are being addressed this year.

The new paper for 2011 extends prior work through a second cycle of iteration, bringing in the experiences of developing a paper for professional peer review, presenting to visiting technical experts from industry, and hopefully, presenting to the airline industry in 2011. It also discusses the experience from a current experiment to close the iterative cycle of improvement: refining the undergraduate high speed aerodynamics course, incorporating the lessons and capabilities learned from the Special Problems research projects and professional papers.

problem formulation

At the center of the concept are the two notions that the market prospects for supersonic airliners should turn out very different in 2010 than in 1990, and that supersonic airliners might lead the air transportation industry into an era of clean and stable growth through early adoption of a hydrogen-fueled airline architecture. Both concepts require considerable concept resilience, given the depressingly pessimistic view that presents itself regarding the willingness of major global corporations and the political leadership towards ambitious innovation other than "cost-cutting". In the cases of the supersonic transport and the hydrogen economy, there are major objections arising both from "facts" established through experience, albeit that from half a century ago, and from superstitions.

Past work [1,2] briefly presented the evidence on why a new look is merited at both these issues. The arguments come from post-1990 global developments in political, economic, demographic and social considerations, rather than from pure engineering science. Briefly, the world is a far different place from that considered by NASA in the 1990s HSCT market projections, which were based almost entirely on western hemisphere routes touching the US coasts. Important and truly massive changes in routes and destinations have occurred in the northern quadrant of the eastern hemisphere, as well in the southern nations of Australia, South Africa and in South America. The opening of polar routes over the former USSR, the trade and travel growth in and from China and India, the opening of South Africa and the economic advancement of Brazil and Australia are leading factors. The steep and continuing rise in fossil fuel prices and the costs of carbon emission, while effectively killing any remaining dreams of fossil-powered supersonic airliners, were seen to be excellent opportunities to bring about an early transition to hydrogen infrastructure, since supersonic airliners would only use relatively few airports.

Ref. [2] laid out a simple conceptual design procedure, compactly capturing the results from the richly detailed procedures used in typical capstone aircraft design courses. This was used to compare the design parameters for a fossil-fueled vs. hydrogen-fueled supersonic airliner to carry 200 to 250 passengers and some high-value cargo, with a range of 8000 kilometers (5000 statute miles). Attention was focused on the Mach 1.4 speed range rather than the higher speeds usually preferred. This is based on the argument that a reduction of travel time to reasonable levels for aging travelers in a point-to-point airline architecture, rather than extreme trans-oceanic speed for hotshot executives on unlimited corporate budgets, is the correct criterion. This in turn brought problems such as sonic boom and stratospheric pollution within solution range. A process was laid out, to convert fuel fraction to per-seat-mile free-market ticket price by looking at the fuel cost portion of typical airline annual report figures (rather than textbook numbers). The common sense of this procedure was validated by comparison with actual free market ticket prices for contemporary transonic long-distance routes. This seat mile ticket price was plotted as a function of the projected cost per unit mass of liquid hydrogen, so that one could see at what cost of liquid hydrogen that fuel would become competitive with various other options at various price points of hydrocarbon jet fuel. The results showed that the Concorde's performance could be bettered (albeit at 70 percent of its speed) at hydrogen costs that are realistic today, and that matching today's transonic business class ticket is not out of the question in the near future. Add to this the key argument that the cost of hydrogen should come down with increasing usage and rising adoption of renewable energy sources for its manufacture, given its unlimited supply, and the prospect of the LH2 SST becomes quite attractive. The issue of development cost remains, as any aerospace corporate executive would wag a finger and remind us that companies are set up to make a profit, not to lose shirts on risky bets. The answer to this comes from the simple fact that a move to renewable-generated hydrogen is the only sure way to achieve permanent reductions in carbon emission for the aerospace industry, and that the carbon market savings from this, for a reasonably sized fleet, would easily pay the development cost of the LH2 SST, even without the substantial national investments that such a technological endeavor would attract.

All of this brings us to the problem formulation for the present paper. The issue now comes down to refining the arguments, and reducing the uncertainty in the above claims. The first area is in predicting the drag of an LH2 SST. The issue here is that liquid hydrogen has a specific gravity of 0.07, versus 0.8 for hydrocarbon fuel. So even with the factor of 3.8 advantage of hydrogen in heat release per unit mass, the volume of hydrogen needed was feared to be so large that it would greatly increase the volume wave drag, and somewhat increase the skin friction drag, at supersonic speeds. The first iteration of conceptual design showed a factor of 2 rise in wave drag coefficient, but a nearly 50% decrease in total drag, because the fuel mass needed was so much less, and hence the payload fraction of the aircraft was far higher with LH2 SST than with the hydrocarbon SST. This estimate was based on the Sears-Haack expression giving the longitudinal distribution of cross-sectional area of the equivalent body of revolution to the aircraft configuration. It was argued that successful design teams would come very close to this ideal, achieving a high Figure of Merit.

This wave drag calculation was the primary subject of attention in the course assignment discussed in this paper. Students in the junior/senior high speed aerodynamics course, which is the last course in the core curriculum on aerodynamics, were asked to form teams of two each (or work alone for no extra credit or consideration) and analyze the aerodynamics arguments presented in Reference 2. They were given the published conference version of the paper, a 1-hour presentation on the topic including the conference presentation accompanying the paper, and copies of several reports and papers related to the topic, as well as links to supersonic aircraft designs done by student teams in NASA competitions. Over the next 6 weeks, they were asked to submit and refine a report each week on the problem. Three central technical objectives were assigned. The first was to refine the minimum-drag body shape and drag value, for the supersonic area rule rather than the transonic (cross sections) area rule. The second was to devise an efficient technique to couple the supersonic area rule method with an engineering drafting tool such as CATIA or AutoCAD, or simpler versions. The latter step is crucial to enable iterative geometry changes, and do the supersonic wave drag computation. The third objective was to estimate the compressible boundary layer drag over the final configuration at the design supersonic and subsonic Mach numbers, and thus refine the conceptual design numbers.

The assignment was laid out in the following steps:

1. Start the report, go through the conceptual design and paper, and develop their own approach to an aircraft configuration including space for the passengers and cargo, fuel, engines, intake and exhausts, wings and tails.
2. Develop a simple cross-section area longitudinal distribution and compare with the Sears-Haack distribution for the same total volume and length constraints. Find the Sears-Haack drag, and the percentage error in the geometries between their design and the Sears-Haack.
3. Compare the Sears-Haack expression for body drag to the wave drag calculated from linear theory over a Sears-Haack body shape. See if second order theory for pressure coefficients does better. Explain the differences.
4. Examine the supersonic wave drag calculation processes discussed in several papers, and explore ways to perform the calculation efficiently by defining appropriate projects in a computer-aided design software package.
5. Implement the supersonic wave drag computation by taking the intercepted area in Mach cones rather than oblique planes. Link the Mach cone procedure to a computer-aided design package and use it to iterate on a configuration shape that minimizes the difference from the ideal Sears-Haack.
6. Calculate the skin friction drag for the final configuration using the Boeing high Reynolds number reference temperature method modified from the Schulz –Grunow method, for the Mach 1.4 cruise condition and a subsonic cruise condition.
7. Submit the final report with the initial and improved conceptual design comparison, and the refined seat-mile cost estimates.

Student performance

This class started with a unique and extreme disdain of "derivations" that had regrettably survived 3 years at our institution, far beyond the resistance usually seen in classes at the junior/senior level. Many students suffered disasters in the first 3 tests because they would not even try to answer any question that required derived logic or proofs. There were of course superlative performers as well, so that the spread in the class grade distribution became quite large. As the above assignment started (after Drop Day, which comes past the middle of the semester), there were many questions asked in class about the prospects for supersonic flight.

One feature of the final reports is that even the students who did not pay much attention to the assignment, actually did some exploration and rationalization regarding hydrogen-fueled supersonic airliners. The best assignments reflected superlative independent thinking and exploration, ("superlative" is not defined as "agreeing with instructor!"). Before going into their own approach they sought and found relevant references from the literature and actually read through them to a good level of comprehension.

The Sears-Haack body shape was easily calculated (see Figure 1 for example), but students ran into trouble when asked to compare the linear theory wave drag prediction with the exact result for wave drag of the Sears-Haack body. This was mostly due to arithmetic or logic errors; typically students used varying values of the reference area and the length in calculating drag coefficients. Thus there was wide divergence in answers, despite the convergent attraction provided by the ideal values and the previous work results. Calculations of the compressible boundary layer drag similarly suffered from wide divergence in the range of answers, with several students declaring that this drag component was negligible. Several teams worked hard on the supersonic area rule, trying to find ways to solve the integral equation. Several different strategies were devised. Next we see what resources they found and used, and their innovations. Layouts were typically revised 4 or 5 times until the designers decided that they could not get any closer to the Sears-Haack ideal. Often this was still quite far from the Sears-Haack and yielded drag as much as 30 to 50% higher.

One student submitted a finely-formatted report, but on close examination it turned out to be a regurgitation of unsupported statements from various "System Design" papers that declared the value of subsonic design optimization, nothing to do with the stated assignment. He was extremely disappointed with the evaluation provided. Another team simply quoted statements from some reference to the effect that hydrogen fueled airliners were far off in the future, with no evidence of any serious calculations. This was reminiscent of "journal reviews" that most of us have seen where the reviewer prefers not to allow mere facts and logic to interfere with their "beliefs". Specific examples are shown below. Figure 1 shows the general shape [3] of the Sears-Haack body, and their configuration, done using CATIA.

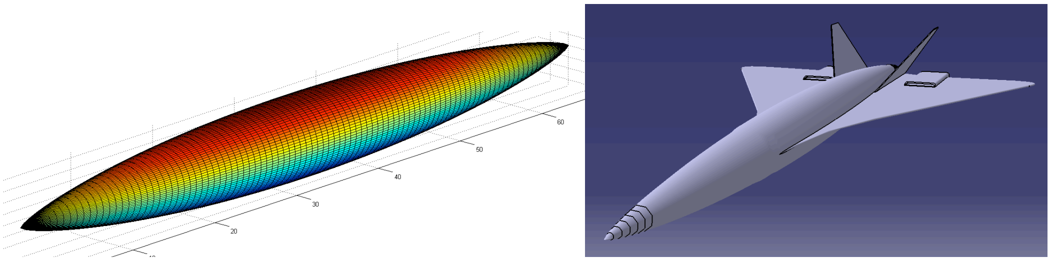

Figure 1: General shape of the Sears-Haack body, and final configuration. From Durbin and Swits [3].

Several assignments went into detail of the supersonic wave drag estimation theory. An example is given by permission [4]. This student also used supercritical airfoil sections for the swept wings.

Problem statement, from Acierno [4]

The drag of the equivalent body of revolution can be computed using Von Karman's formula:

$$D_{M\to 1} = -\frac{\rho V^2}{4\pi}\int_{-x_0}^{+x_0}\int_{-x_0}^{+x_0} S''(x)S''(x_1)\log|x-x_1|dxdx_1 \tag{3.1}$$

Where S(x) is the function describing the equivalent body of revolution in terms of normal cross-sectional area vs. location along the x axis. S can be derived from the oblique cross sections obtained by the intersection of Mach planes with the wing-body combination through

$$S = s\sin\mu \tag{3.2}$$

Where s is defined as the area intersected by the oblique Mach planes. As detailed in reference 5, S'(x) may be expanded into a Fourier series and described as:

$$S'(x) = \sum A_n \sin n\Phi \tag{3.3}$$

While allowing x to be described as $x = x_0\cos\Phi$, an explicit equation for the wave drag of a wing-body combination at supersonic speeds can be shown:^{5}

$$D = \frac{\pi\rho V^2}{8}\sum nA_n^2 \tag{3.4}$$

The process of iterating the cross-section area with components included, is captured in Figure 2, from Dessanti and Ingraham [5] by permission.

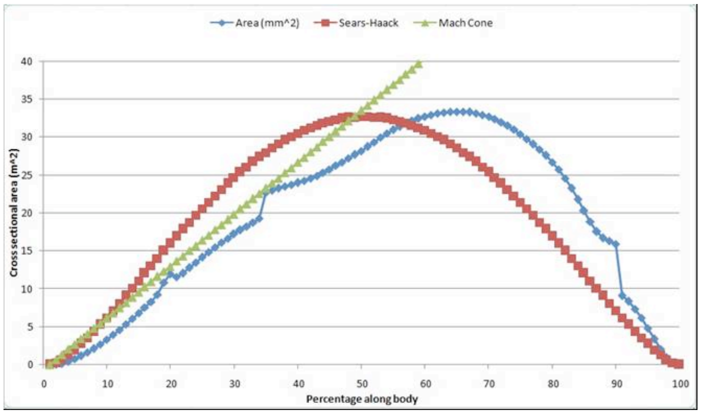

Figure 2: Iterations on the configuration area distribution. From Dessanti [5]

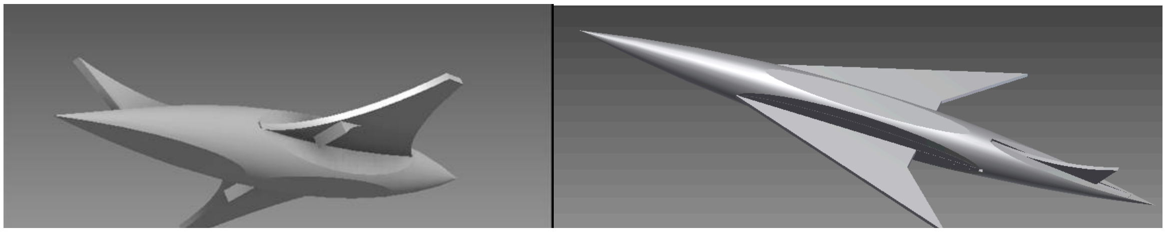

Figure 3: Configuration before and after supersonic area ruling. From Durbin and Swits.

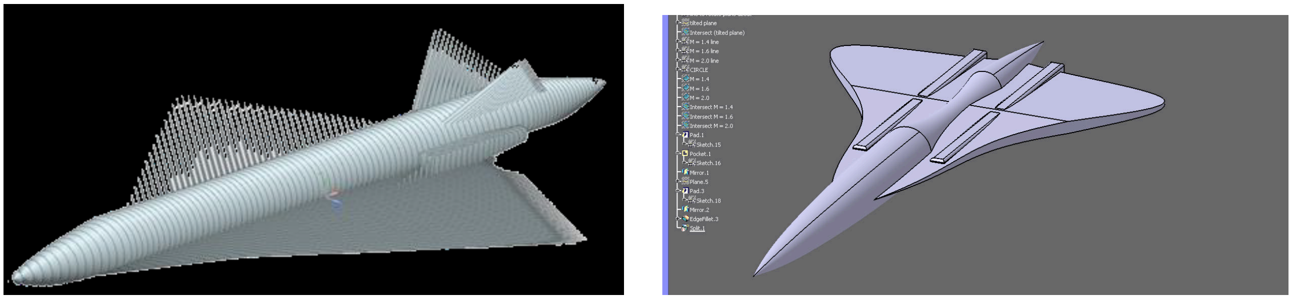

Figure 4: Configuration, and process for Mach cone section area determination. From Cornish and Cornell [6].

Figures 3 and 4 illustrate the starting configuration used by one team, and the modified configuration after supersonic area ruling. Figure 4 shows the final configuration from another team [6], along with an illustration of the process they used to rapidly obtain Mach cone intersection and projected areas, integrated with an open-source interactive graphical design software package.

Table 2: References used by students

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assessment results

This course provided a study in contrasts. As mentioned before, the cohort at the start of the semester appeared to have reached the final course in aerodynamics, quite remarkably untouched (relative to 25 years of the instructor’s experience in the same institution in the same subject area at the same level) by the need to take notes in class, read and understand derivations, ask questions in or outside class, attempt worked examples or old question papers, put real effort into assignments, or pay attention to the stated requirement of punctual and regular attendance. No doubt this raised some interesting challenges. These were partly addressed through:

1. Willingness to assign negative grades for writing total nonsense on answer sheets (i.e., for special efforts such as the speed for minimum drag of the NASA Solar Pathfinder aircraft being 9000 feet per second calculated through incompressible aerodynamics, or for drag coefficients of over 25). This brought a question about the fairness of this grade, phrased as “what would he have got if he had not shown up”, the answer being “a zero and a request to drop the class and quit wasting everyone’s time”. Apparently this issue was also debated at local Co-Op employer workplaces, leading to much merriment and total lack of sympathy among the practicing engineers there.
2. Failing grades on assignments where the entire submission consisted of an uncommented MatLab code M-file, regardless of the claims of completeness and correctness of said code.
3. Tests set with 20% additional questions beyond what would have been reasonable for the given time period, with the maximum score set at 120 percent.
4. A class average and median scores on the first test below 20 percent, with a blunt refusal to state any such number in class, since there was no “curve grading”. People who demand “curve grading” are usually not accustomed to the idea of thinking, enough to understand why it is kind NOT to do curves where the top score is 119 out of 100.
5. A “surprise quiz” with 12 short questions, in a well-announced regular Friday class when the instructor was out of town, but students had been specifically requested to attend. In this case none of the absentees even bothered to enquire about the prospects getting anything above zero, showing that some independent reasoning ability was being gained.
6. A second official test where it became clear that there were to be no miracles or partial credit when derivation questions were left blank, providing the desired outcome of a good number of Course Drops.
7. An announced practice of grading team assignments differently for each team member, based in part on their answers and performance on tests where a large part of the grade depended on

specific questions about their assignments. (For instance, a team member who declares: "I don't recall what the specific drag number was, but I do remember that the weight was 3.57 million Newtons and the lift was 1.27 million Newtons, and I assumed Straight and Level Steady Flight" does not merit an A assignment grade regardless of how good the team assignment appears to be).

Major improvements in attitude took time, but do appear to have occurred, given the superior quality of effort on the final assignment, and the resulting superior performance on the final comprehensive test by about half of the original cohort. Sadly, but perhaps inevitably if one is to avoid depressing those who put in excellent thought and effort, there were no miracles for those who simply could not raise their "game".

discussion

As glimpsed above from the examples of work, and especially from the long list of references (many are not cited above because they were too incomplete to cite) that the students found, read and used, a Concept Development exercise does bring out the best in many students. The concept of supersonic area ruling is difficult, as evidenced by continuing publications in AIAA conferences of funded project results seeking to improve the iterative procedure. Tying everything together in a conceptual design, while focusing on supersonic configuration aerodynamics, is a demanding exercise when one is also taking some 13 other credit hours of demanding courses. In this context, one has to admire the enthusiasm, initiative and efforts shown. The top 50 percent of these assignments are truly impressive.

On the other hand, one major change that occurred this semester was the decision to not let the top students be dragged down by students who had reached the penultimate semester in the curriculum on mental "cruise control". Sadly for these students, there was no miracle, the wide disparity in performance making end-of-semester summative evaluation quantitatively easy, as emotionally difficult as it may have been.

The above process now completes the second iteration of the concept development process. What started as a question on demographics and carbon market issues, went through the first iteration to show viability with top-level conceptual design and aerodynamics in 2009-2010, using course assignments to train some students, but resulting in 2 peer-reviewed publications. In the second iteration, the aerodynamics issues were refined, and the students added a large knowledge base on the other issues which remain to be studied, such as the usability and cost projections for liquid hydrogen, sonic boom alleviation technology, and much more detailed configuration aerodynamics and internal layout issues. The variety of procedures to couple CAD software with supersonic area ruling theory, is a major boost to our capabilities, that must be integrated in the EXTROVERT knowledge base. The next step may be to refine the sonic boom issues and alleviation techniques at the graduate course level (Spring 2011), before returning to future iterations where drastically different configurations can be investigated.

Tough problems remain in all aspects, but this is not surprising. It is just that such an exercise removes the superficial appearances and cuts into the issues enough to reveal and address these problems.

conclusions

This paper describes a second iteration of an Advanced Concept development project. Students in a core undergraduate aerodynamics class were asked to understand the essential issues and concept development approach from a paper done by their predecessors, and were provided with a challenging problem specification and professional level literature. One conclusion is that this exercise brought out a broad spectrum of responses, both technical and innovative.

The exercise brought out the large dynamic range in the skills, capabilities and thinking experience of students one semester away from graduation. This resulted in identifying areas for substantial pre-graduation improvement in several students (up to half the class in this case), but also showed what the students as a whole are capable of doing, which is very impressive. Several innovations and the large amount of knowledge captured from the course set the stage for professional level advancements in the area of supersonic aircraft development and aerodynamic design.

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