THE POWER OF MATHEMATICS AT 1000 MPH

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Project BLOODOUND

The theme of the AMESA Congress 2014 is demystifying mathematics. The challenge we face when working with learners of all ages, in particular grades 4 to 9, is how to make the subject interesting, exciting and even **fun** in the classroom. Sadly, the result of this failure to excite is a worldwide shortage of scientists, engineers and mathematicians who will need to come up with answers to the global challenges we face that include shortages of energy, clean water and food, health, security and global warming to name just a few.

There was a terrific increase in the number of science and maths graduates worldwide as a result of the US moon landings programme of the late 1960's and early 1970's where youngsters were fascinated by the enormous challenges answered by the scientists and engineers at NASA. The BLOODHOUND education programme would like to create a mini Apollo effect and create a surge in learners wanting to become the next generation of scientists and engineers. This is the number one aim of the BLOODHOUND Project, and not surprisingly, to break the current World Land Speed Record (WLSR)! In fact it was a requirement set by the UK government that we develop an education programme to overcome the countries shortage of scientists and engineers. They would then loan us the world's most powerful lightweight jet engine, the Eurojet EJ200, and in itself an amazing piece of engineering jewellery.

The BLOODHOUND SSC project was launched in October 2008 with the engineering objective of designing, building and running a car to achieve a new WLSR of 1000 mph. This engineering objective is coupled with the primary objective to promote science, technology, engineering and mathematics (STEM) to schoolchildren in the UK and beyond via the BLOODHOUND education programme. Clearly, the aerodynamic challenges associated with developing a land-based vehicle capable of safely achieving speeds of up to 1 690 km/h (1 050 mph and approximately Mach 1.3) are great, particularly at supersonic speeds and only ever achieved previously by one vehicle – ThrustSSC in 1997 – 17 years ago! Drag minimisation and vertical aerodynamic force control are of paramount importance for a safe record attempt on the constrained distance of 20 km available at the record attempt site of Hakskeenpan in the Northern Cape. Computational fluid dynamics (CFD) were chosen as the primary tool to guide the aerodynamic design of the vehicle as was the case in in the 1990's when the mathematical technology was in its infancy.

The CFD system used for the BLOODHOUND study was the Swansea University FLITE3D system. This is a classical cell-vertex finite volume method, with stabilisation and discontinuity capturing, implemented on hybrid unstructured meshes. The next few paragraphs briefly describes the CFD process used to analyse such a complex aerodynamic problem but its focus is on the predicted aerodynamic behaviour of the final frozen design (known as configuration 12 – abbreviated to config12) of BLOODHOUND SSC. It outlines both the on and off-design aerodynamic characteristics of the vehicle and considers the impact of different engine conditions and directional stabilities.

Figure 1: 2007 artist's impression of the 'yet to be named' BLOODHOUND World Land Speed Record vehicle.

The BLOODHOUND SSC aerodynamic problem

In the past three decades, CFD has revolutionised the way in which the aerospace industry tackles problems of aerodynamic design. In particular, unstructured mesh methods now allow grids on complex 3D geometries to be generated in a matter of hours, which might once have taken several months using multi-block techniques. In light of this, CFD has become an integral part of the typical aerodynamic design cycle.

On the BLOODHOUND SSC project, for practicality, financial restrictions and time constraints, the major design cycle loop has focused on the actual vehicle runway and desert testing. This is where validation of the CFD modelling used will take place. It will be the case that initial vehicle runs on Hakskeenpan in 2015 will lead to significant re-design work ready for the target speed of 1,000 mph in 2016.

The major design changes that have taken place during the design cycles as a result of aerodynamic modelling are shown in Figure 2 below.

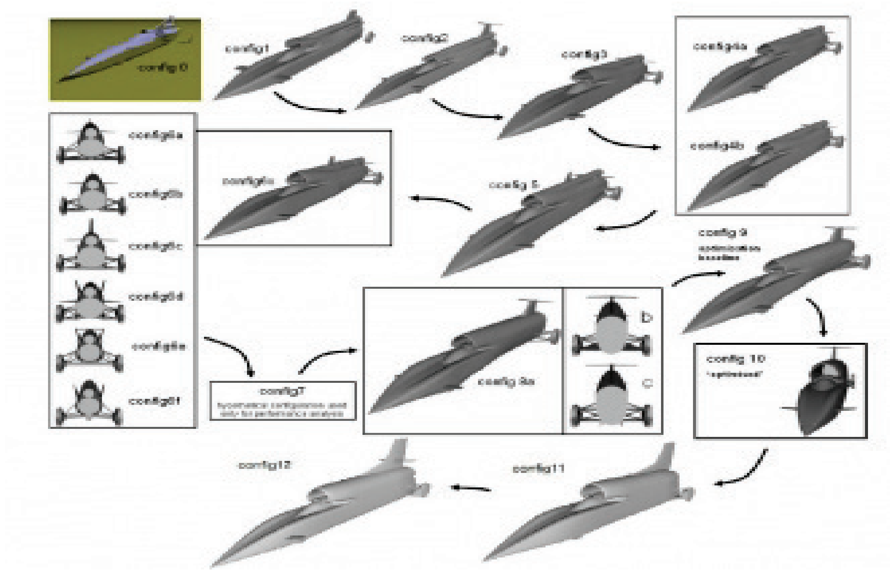

Figure 2

1. Between config 0 and config 1, a transition was made from a design with a twin (bifurcated) jet intake to a design with a single jet intake. This change was made to improve the 'quality' of the flow at the jet compressor face across the Mach range. The front wheels also moved from a staggered configuration to a symmetric configuration.[15]
2. Between config 1 and config 4, the positioning of the rear winglets and the vertical fin was varied, and the rear suspension was designed and included in the CFD model.
3. Between config 4 and config 6, the rear-wheel suspension geometry was varied together with the body shaping as a result of internal packaging constraints. The size and area distribution of the jet intake were also varied.
4. Config 7 existed only as a hypothetically perfect vehicle from an aerodynamic performance point of view. These hypothetical data were used in the overall vehicle performance model as a baseline case to give an indication of criteria such as the required track length for vehicle testing.
5. Config 8 introduced the rear 'delta fairing'[22] for supersonic lift minimisation at the rear of the vehicle.
6. Between config 9 and config 12, a series of parametric optimisation studies was carried out together with an increase in the fin size to achieve the directional static margin target.

The BLOODHOUND design engineering team was setting out to do something truly extraordinary. This wasn't just designing a new airliner, for example, where they could build on vast amounts of prior knowledge (Comet, Boeing 747, 777 or Dreamliner, Airbus A350 or A380), by making marginal gains to create the next generation. The sheer audacious ambition of increasing the current WLSR by over 30% meant that they had to start from a blank sheet of paper and not only design a new type of land speed record vehicle, but also develop a whole new way of design thinking.

Of course, the question of '*can we keep the car on the ground*?' was an early topic of conversation, but they could never have guessed that this problem would cause far more of a headache at the rear of the car, than just keeping the nose down at the front. This unforeseen aerodynamic behaviour led to the six month rear suspension optimisation study that resulted in the 'delta fairing' design which has been a feature since 'config 9'. In those early front room conversations they hadn't anticipated that getting the twin intake bifurcated duct in the original design to deliver a suitable flow to the EJ200 compressor face across the entire Mach range would be so difficult - another mathematical design challenge for the team. Of course, this eventually led to revert to a single intake above the cockpit canopy, causing significant structural headaches to be overcome. In those early days the team had no real 'feel' for how directionally stable the car would be, which in turn meant they didn't really have an idea of how big the fin would need to be to 'keep the pointy end heading forwards'.

In fact, for the first few iterations of aerodynamic design, where they almost completely focused on the question of what the external shape of the vehicle should be like, but still answering the question '*is 1000 mph even possible?*', They were constantly being surprised by the aerodynamic performance that the CFD simulations were predicting. That was a little nerve-wracking for the team and the driver! Of course there were things the team could do to investigate the causes of odd aerodynamic phenomena, such as flow visualisation. This led to some of the famous BLOODHOUND imagery that has been available over the years (e.g. Figure 3) and force distribution breakdowns. This has allowed the team (in the virtual world) to gain a far better understanding of how BLOODHOUND SSC will behave when testing commences next year.

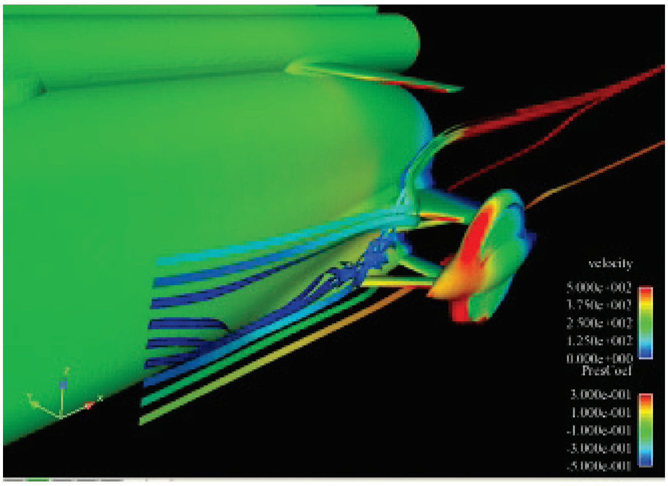

Figure 3: CFD flow visualisation of the complex flow around the rear wheels of BLOODHOUND 'config ***4'***

The aerodynamic team has really been on an astounding journey of engineering design research. Figure 2 shows the journey of design evolution from 2007's 'config 0' through to the 'config 12' design that is currently being built in Bristol in south west England. One thing that you should be able to spot from this view of the design evolution is that they were 'homing in' on the optimum shape where the geometric shape changes get smaller and smaller. Anyone who has used any form of trial and error, which is essentially what we do in engineering design, will be familiar with this pattern. But, more importantly, what else has been happening is that the aerodynamic effect of making changes to the geometric exterior has become more and more predictable.

In fact, with the most recent and subtle changes to the exterior of the vehicle, Ron Ayers and Ben Evans have been able to confidently predict the impact on aerodynamic performance intuitively and have then used CFD simulations as a 'double check'. For a mathematician this is a much happier position to be in than the early days of 'running the CFD blind' and then crossing fingers that we could make sense of the data that came back. CFD and intuition are now working together in partnership!

Of course, the question, now that we leave the virtual world behind and turn our eyes towards running in the reality of testing on Hakskeenpan, is whether or not this *path to predictability* will continue.

This insight into the aerodynamic design challenges faced by the engineering team has been one major chunk of the jigsaw, but one that had to be completed prior to any build could take place. Hence the delay of four years in coming to South Africa. As you can imagine the driver was reluctant to sit in the car and attempt the WLSR without confirmation it would stay on the ground and travel pointy end first!

There has also been major research carried out on a car's component that most of us take for granted - the wheels! The four wheels on BLOODHOUND SSC are 90 cm diameter and have a mass of 95 kg each. They rotate at 10 300 rpm, that's 171 revolutions per second and generate 50 000 radial g at the rim. If you were to place a 1 kg bag of sugar on the rim, at 1,000 mph that bag of sugar would weigh 50 000 kg. So just with the wheels there is very exciting mathematics involved that has kept major universities and international companies occupied for some time! Plus the engineers needed to consider what would happen if a small stone from the pan surface kicked up and collided with the car at supersonic speed. So they had to investigate the ballistics of such incidents and the gas gun at Cambridge University came in very useful.

So what else was going on with the mathematics and science associated with travelling at very high speeds? Well think about what happens to air flowing around the sides of the car at high speed. Above approximately Mach 0.3 (a third of the speed of sound, or roughly 320 km/h) air begins to take on the important property of compressibility. This means that air can not only change direction to navigate around an obstacle, but it can now also 'squeeze' or compress to help it on its way. The extent to which this compression, and associated density rise occurs, depends upon the speed of the air relative to the speed of sound and the shape of the object it is trying to make its way around. The reason BLOODHOUND SSC is long and thin is to try and reduce the extent of this compression as this usually translates into drag. The ultimate expression of air compression is a shock wave, within which this compression occurs almost instantaneously and manifests itself in the supersonic 'BOOM' and the beautiful pictures of the THRUSTSSC, see Figure 4

Figure 4 – The supersonic shock wave emanating from the nose of ThrustSSC and showing up late in the afternoon intensified by a dust storm earlier in the day.

The mathematics of science

Now imagine yourself as an innocent particle of air in the path of BLOODHOUND SSC travelling towards you at 1 610 km/h (roughly 1.3 times the speed of sound). First of all you will have to navigate around the nose of the car by squeezing/compressing/slowing down through a shock wave (the bow shock on the car). Once you have successfully avoided the nose, you can then, briefly, accelerate down the side of the car until you meet air coming at you from above the cockpit canopy that itself has had to 'shock' and squeeze past the canopy and upcoming jet intake duct. This has caused you to have to change path, compress again in a shock wave and slow down. You have now survived this second interruption to your day and you are given the opportunity to accelerate down the side of the rear half of the vehicle until something rather ominous approaches you – one of the rear wheels. Just when you thought you were home and dry, you have to experience a third shock, which turns out to be the strongest shock of all. The density of the air through this shock wave almost doubles, and it is this that gives rise to high pressure at the front of the rear wheel fairings and also the source of our huge rear supersonic lift.

Figure 5. BLOODHOUND SSC config10 top – note the long and slender shape to minimise air compression and hence drag.

All we can provide at the AMESA Congress is a brief insight into the leading edge research associated with a car designed to travel at 1 690 km/h. Almost every education subject can be enhanced by using BLOODHOUND as an exciting context for learning. The choice of Hakskeenpan, the culture and history of the local Mier people, how to develop tourism opportunities, writing press releases and using dramatic language to describe the drivers experience – all opportunities for educators to use BLOODHOUND in the classroom. The challenge that educators now face is how to expose as many learners as possible to the excitement of engineering, which is based so centrally on mathematics. Teachers are the key to economic success and prosperity in every country.