Industry applications of advanced flow diagnostics experience in the BAE Systems ground effects rig

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ABSTRACT

This paper reviews some of the work performed on the ground effects rig at BAE Systems in Warton, the now unique facility for modelling dynamic vertical landings and measuring hot gas ingestion. The paper discusses the flow diagnostic tools which have been used in recent times, up to the complexity of 3D PIV, and uses examples from the F-35 JSF programme to illustrate these. The paper hopefully demonstrates the difficulties of using these tools, as well as the benefits they can bring to a development programme.

The ground effects rig is a facility designed to measure temperature rise in aircraft intakes during vertical manoeuvres close to the ground. It is a complex facility that comes as close as possible to accurately modelling the flowfields around an aircraft moving both vertically and horizontally near the ground, with the ability to model dynamic pitch and roll at the same time.

Standard instrumentation for the models consists of rapid response thermocouples mounted in a rake at the engine face. 45 thermocouples of 0·05mm diameter with a time constant of about 10ms are used.

Although, with its standard instrumentation, the rig can measure how much hot gas gets to the engine face, it doesn't show how it got there, or where it came from, which is the knowledge required to improve the design. Hence there is a need for flow diagnostics.

NOMENCLATURE

AGF	advanced gas facility
CFD	computational fluid dynamics
GER	ground effects rig
HGI	hot gas ingestion
JSF	Joint Strike Fighter
PIV	particle image velocimetry
T	temperature
T_{amb}	ambient temperature
3BSD	three-bearing swivel duct
θ	excess temperature (T–T_{amb})

1.0 INTRODUCTION

The phenomenon of hot gas ingestion (HGI) is of high importance for jet powered vertical lift aircraft. Simply put, the ingestion of hot exhaust gases into a gas turbine engine leads to a reduction of maximum available thrust, while the distribution of temperature around the engine face can lead to a reduction of engine stability. Depending on the level of ingestion, the reduction of maximum available thrust can normally be managed: opening the throttle a bit further will restore thrust under normal conditions. However, if the engine is already at maximum thrust, or in high ambient temperature conditions, any ingestion will be a problem. That is, HGI becomes a problem at exactly the conditions where you need maximum thrust.

The reduction in engine stability due to temperature distribution, or distortion, is analogous to the effect of pressure distortion. If a threshold value is exceeded then the engine will surge, leading to a very high loss of thrust and possible damage to the engine (let alone the damage to the aircraft if it happens during a hover). The distortion has only to last half of one engine revolution to cause a surge.

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The flowfield around a vertical landing jet lift aircraft is extremely complex. Out of ground effect the various lift jets and the associated entrainment field are fairly steady. Once the jets impinge on the ground they set up ground jets, which interact with each other to create fountain flows and reinforcement regions, all of which are extremely unsteady. In addition to this the aircraft is also moving vertically, thus changing the boundary conditions of the flowfield. The resultant flowfield is too complex for CFD analysis at present and requires experimental modelling.

BAE Systems has a special facility[1] for modelling vertical aircraft manoeuvres and measuring the resultant hot gas ingestion. However, sometimes it is not enough to simply measure the resultant ingestion; measurements are needed within the flowfield to aid the understanding of the phenomena being modelled, and help to prevent their occurrence.

This paper will briefly describe the facility and give some examples of different flow diagnostic measurements taken during the development of the F-35B JSF aircraft.

2.0 THE GROUND EFFECTS RIG

The BAE Systems ground effects rig (GER)[1, 2] is a purpose built facility for exploring HGI and suckdown in vertical manoeuvres in the vicinity of the ground. It has been in operation for just over 20 years, initially at Kingston, and latterly at the Warton site, near Blackpool in the UK. During that time it has been continuously improved and upgraded.

The basis of the rig is a hydraulically controlled pantograph mechanism that allows the aircraft model to be moved anywhere in a roughly square vertical/longitudinal plane. The pantograph allows for the modelling of creeping vertical landings and creeping vertical take-offs, as well as purely vertical manoeuvres at full scale speeds. Hydraulic actuators at the model mounting point allow pitch and bank angle to be remotely set and controlled between, or even during, manoeuvres. Model scales of between 1/10th and 1/15th scales are accommodated, and are served by three independent heated air supplies and one suction source. The two main heating supplies are hydrogen fuelled, and are capable of operating at up to about 450°C. A third, electrically heated, supply was added with the advent of the JSF configuration. The suction source connects to the intake.



Figure 1. General view of ground effects rig.

The main instrumentation for the rig consists of an array of 45 very fast acting thermocouples at the engine face. These 0·05mm copper-constantan open bead devices have a time constant of about 10ms, which is necessary to capture the transient temperature distortions which can lead to surge. The instrumentation is scanned at 250 samples/s, but even at these rates and with these fast response times it is still necessary to correct for thermocouple lag.

Figure 2 shows an example of the output from the engine face thermocouples after lag correction. The value θ is defined as being the excess temperature, i.e. the temperature above ambient. In this case, at a height of 2·89m, it can be seen that there is some ingestion in the lower half of the engine face, thus coming from the main intake rather than the auxiliary intake. The data from the individual thermocouples are used to determine engine face averages and temperature distortions.

The facility is situated in a dedicated large volume building, and has a large diameter fan to provide wind simulation. The fan can be swung through a 90° arc to provide headwind and crosswind simulation, and can be controlled from speeds of two knots to 30kt. It has a flow conditioning package to remove the fan swirl and provide a simulated ground boundary layer[2]. Hot gases are ducted out of the facility before and between tests by an underfloor extraction system. Despite this, the mean ambient temperature rises in the facility during the course of testing. This is accounted for by taking a datum scan of the instrumentation immediately prior to test. All temperatures are then measured as deltas relative to ambient.

3.0 SCALING CONSIDERATIONS

The subject of scaling for HGI testing has been investigated since the 1960s[3-7]. The most obvious limitation of the experimental rig is that it cannot match full scale temperatures, being able to reach approximately half that value. However, further investigation shows that even if it were able to reach full scale temperature, it wouldn't be able to match the correct buoyancy of the hot flows, due to the sub-scale nature of the model and the inability to scale gravity.

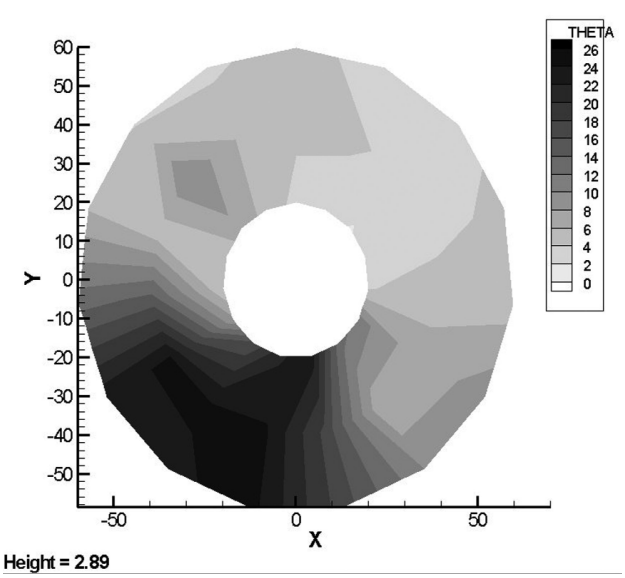


Figure 2. Excess temperature at engine face.

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One of the consequences of running at full scale nozzle pressure ratios with small scale models is that time also scales, with real time being faster than model time. This makes it all the more important to have very fast thermocouples.

Blogg[7] gives a full explanation of scaling matters, backed up by both experimental and CFD evidence. We are very confident in our ability to accurately set-up scaled temperature conditions, and convert measured temperatures to full-scale.

4.0 THE JSF HGI MODEL

The model is scaled to an existing engine face thermocouple array, and as such comes out at 1/13·87 scale. The rear nozzle has a working three-bearing swivel duct, so can be set to any desired vector angle. The front Variable Area Vane Box nozzle and the roll post nozzles have fully representative geometry.

The model has fully representative lower fuselage lines, but some approximations have to be made on the upper surface to enable gas to be supplied and extracted.

One of the most obvious approximations in the model is that the lift fan is represented by a fixed supply of heated air entering the model at the lift fan inlet. This obviously compromises the detail of the flowfield into the main engine auxiliary inlet, located just behind the lift fan, but was the only practical way of modelling this for the bulk of testing, where the ingestion into the main engine was being investigated.

A development of the model has been to commission the development of a turbine powered simulator (TPS) for the lift fan. This has been undertaken by Microjet Engineering (www.microjeteng.com), based in Cambridge, UK. The unit consists of a two-stage counter rotating fan driven by tip turbines fed from an annular plenum around the unit. Because of the scale of the unit it was always recognised that it would not give the full scale nozzle pressure ratio, and would also not have the right scaled temperature. Careful scaling of the momenta for all the nozzles and wind, plus changes to time scaling, allow tests to be undertaken at reduced pressure. When the TPS is fully commissioned and installed in the model, we are able to take temperature data at the lift fan entry and main engine face simultaneously. Figure 4 shows a picture of the top view of the unit, with the thermocouple rake installed above it. Although the thermocouples are not installed in this picture, they would not normally be visible anyway, due to their very thin diameter.

5.0 FLOW DIAGNOSTICS

A range of flow diagnostics can be used at the facility, ranging in complexity and cost from the very quick and simple to the rather

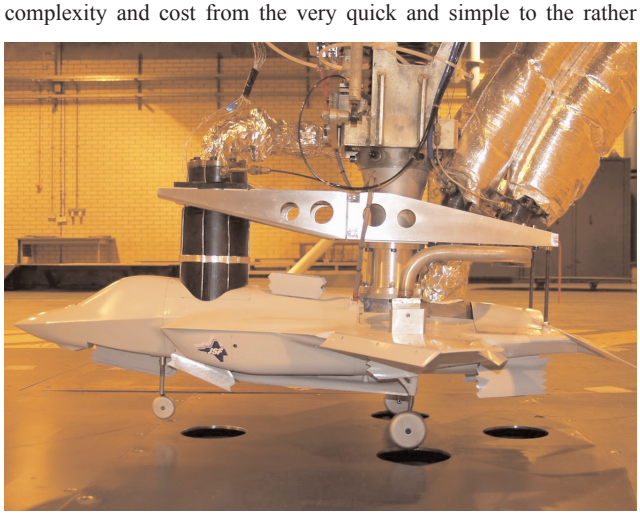


Figure 3. JSF model mounted on rig.

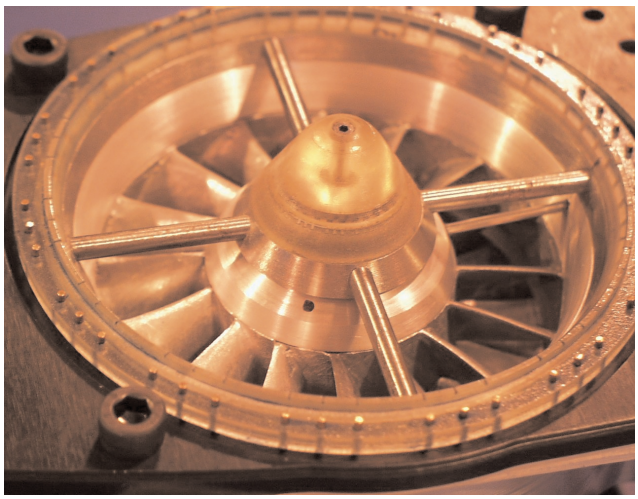


Figure 4. Turbine powered simulator top view.

complex. The simplest, and often most revealing, technique is the wandering tuft. Having a wool tuft on the end of a wand, which can be manoeuvred around the model, allows the engineer to get a good appreciation of the three dimensionality of the flowfield. Unfortunately, this technique can only be used in the GER when only the suction is running, it being too dangerous to enter the facility when the high pressure lines are powered up for the nozzles. Nevertheless, the wandering tuft gives a very good appreciation of the flow into the intakes, where dividing streamlines are, relative suction strengths, presence of vortices, etc. A variation on this theme is the smoke wand, which can be used to visualise streamlines.

Fixed tufts taped to surfaces allow flow directions to be visualised from outside the facility with the jets switched on. The obvious disadvantage is that they need to be on a surface. It is possible to fix tufts to a fine wire mesh in order to get flowfield visualisation, but such meshes are cumbersome to use and manoeuvre, and it is difficult to get good camera angles to make use of the information.

Another surface based diagnostic tool is the use of oil flow visualisation. This has mostly been used to look at impingement zones and to track stagnation lines on the ground. Some use of the technique has been made by painting models, to track fountain flow impingement. Figure 5 shows an example of the ground flow technique from JSF testing. The crosses in the picture show the approximate

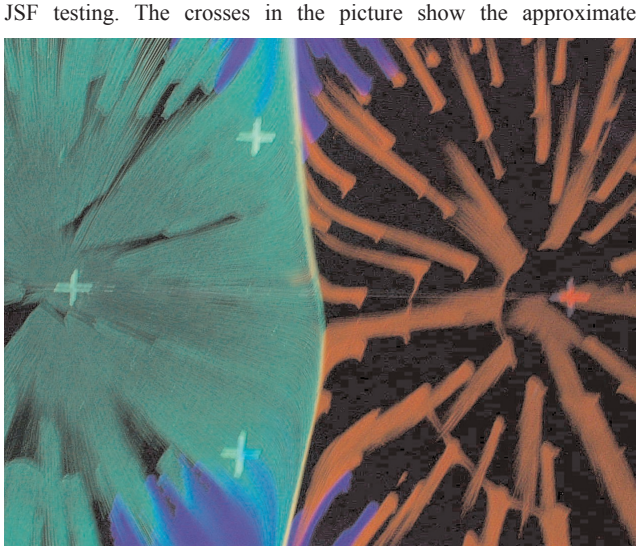


Figure 5. Oil flow visualisation of ground flows.

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positions of the impingement points of the jets. The front jet flow is to the right of the picture. It can be seen that there is a slight asymmetry in the ground flow, with the most forward penetration of the rear jet being offset slightly to the right side of the aircraft. This is consistent with an asymmetry in the rear nozzle flow caused by the geometry of the 3BSD. Surface oil flow gives only two dimensional data on a surface and can at best only hint at any three dimensionality in the flow. This picture does not show the trajectory of the fountain flow once it leaves the ground.

5.1 Laser sheet visualisation

Another often used technique is laser sheet flow visualisation using either externally generated smoke, or water injected into the jets. Laser safety regulations mean that viewing such visualisation techniques must be done remotely by CCTV. Low light cameras are needed to generate enough detail in the image, and a good deal of trial and error is used to get suitable views. Figure 6 shows an example of water injection visualisation. Water was introduced into the rear jet only, although some spray has been entrained into the front jet. The laser sheet extends along the centreline of the model. As a still photograph, this picture doesn't convey much information. As a video, it graphically conveys the unsteadiness of the fountain and, to a lesser extent, the rear jet itself.

5.2 Infra-red flow visualisation

It might be thought that the use of infra-red imaging would be an ideal technique in the situation where we are trying to track hot gas flowpaths. Unfortunately, the use of hydrogen as fuel considerably reduces the usefulness of this technique. In order to 'see' hot gas in the infra-red spectrum there needs to be some carbon present, either in the form of carbon particles or as carbon dioxide (depending on the particular waveband). Hydrogen only produces water as a product of combustion, so is invisible to infra-red. Imaging cameras can therefore only see hot surfaces. An example of where this was particularly useful is given a bit later in the paper.

5.3 Particle image velocimetry

An answer to the problem of getting both qualitative and quantitative data from the flowfield around the aircraft is to use PIV. Such systems have traditionally been able to give 2D velocities in a planar slice. Recent developments now allow the assessment of cross-velocities normal to the slice.

An assessment of the use of PIV was made in the GER during 2003, and this will be dealt with in more detail later.

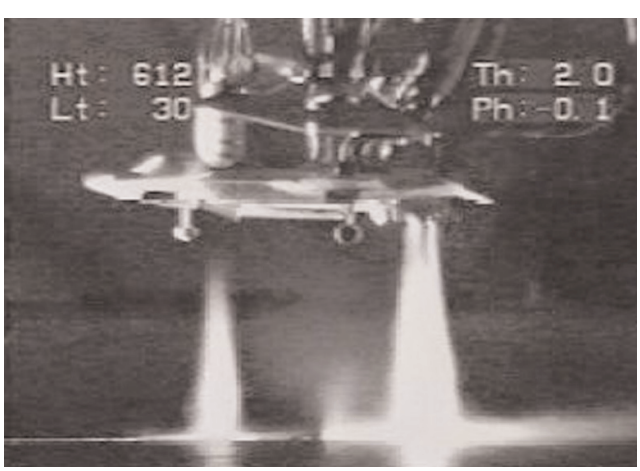


Figure 6. Laser sheet visualisation of water injected into the rear jet.

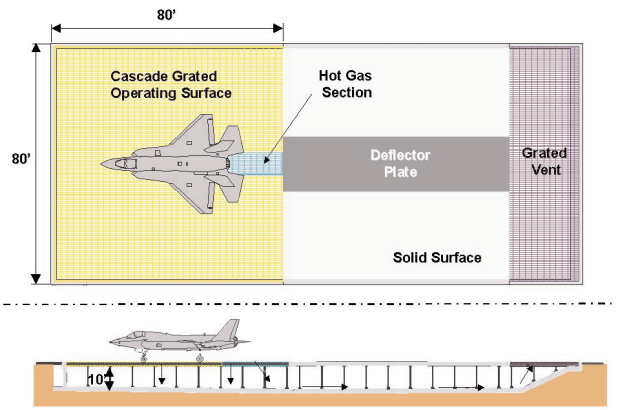


Figure 7. Diagram of initial hover pit design.

6.0 HOVER PIT INVESTIGATION

A recent test campaign, using the JSF HGI model in the GER, was to assess the suitability of a hover pit design, to be constructed at Lockheed Martin's facility in Fort Worth, Texas. The hover pit is intended for use during checkouts of the STOVL aircraft lift system, and for vertical flying manoeuvres. A well designed hover pit prevents the creation of ground jets and fountains, thus reducing suck-down effects and hot gas ingestion. The intention is to duct the hot gases away from the aircraft and prevent them returning.

A successful hover pit had been built at Lockheed Martin's Palmdale site in California for the X-35 aircraft[8], and a slightly enlarged version of this was used as the baseline standard in this investigation. Figure 7 shows plan and cross-section of the pit, including the initial sizing options to be considered. Pillars from the floor of the pit support a series of turning vanes, which in turn support a mesh on which the aircraft sits. The vanes turn the flow towards the exhaust, which has a series of exit vanes. A solid section between the pit and the exhaust was made available for testing.

Being a fixed installation, the hover pit needs to work effectively over a range of wind directions and speeds, and with different orientations of the aircraft on the grid. For the model testing this meant that both the pit and the fan needed to be able to rotate independent of the model and each other. Figure 8 shows a picture of the installation. In this case the pit is rotated to 90°, the short solid section is installed and the exit turning vanes have been removed.

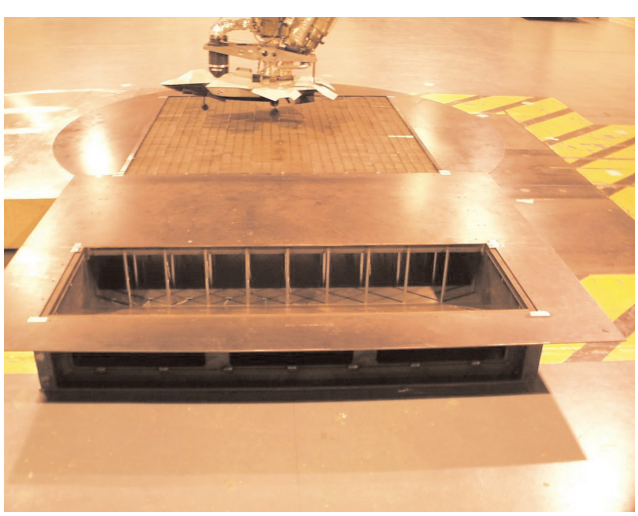


Figure 8. Hover pit model.

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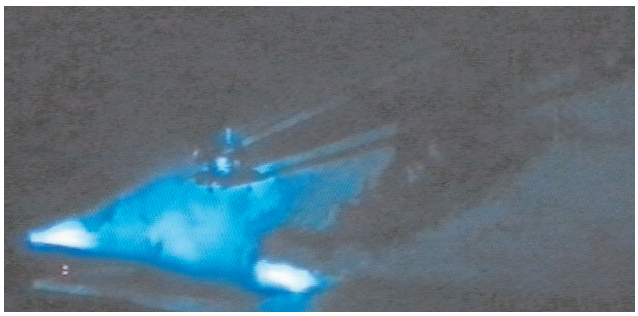


Figure 9. Smoke flow visualisation.

Early tests with the HGI model revealed unexpected levels of ingestion, particularly at hover heights around 30ft. Although the model instrumentation could measure this, it gave no indication of what flow phenomena were causing this to happen. Laser sheet flow visualisation and IR camera pictures were needed to help decipher what was happening.

The best results for laser flow were obtained by introducing smoke near the front edge of the pit and having vertical laser slices parallel to the aircraft axis. This technique was able to show where the pit was pumping (flow being sucked into the pit) and where it was leaking (flow escaping the pit), but still did not give enough information about why it was leaking where it was.

Figure 9 shows a still from the flow visualisation video. Here the laser is behind the model and aligned slightly to one side of the centreline, so that the main nozzle flows are not visible. The intense reflection at the back of the view shows the flow from the hover pit exhaust. The bright reflection at the front of the view shows the presence of a trapped vortex at the front of the pit. Beneath and just behind the aircraft there seems to be a surprisingly high quantity of hot gas rising out of the pit, which doesn't really match with the temperature measured at the engine face. It is very difficult to get much information from a still photograph. The video footage is more revealing, but still only qualitative.

Further insight into the flow was obtained by using an infra-red imaging camera. This camera was working in the 8-12μm waveband and able to show temperatures of the model surfaces. As mentioned previously, the jets themselves were not visible. Figure 10 shows an image taken during a landing onto the pit. In this instance the pit is oriented at 0° to the model and there is a solid extension piece between the pit and the exhaust (which is not visible). This configuration was the shallowest pit depth tested.

The model can be seen to vary in temperature from cool at the nose, through to very hot at the rear nozzle feed. The main wheels can be seen to be quite warm, and a reflection of these can be seen

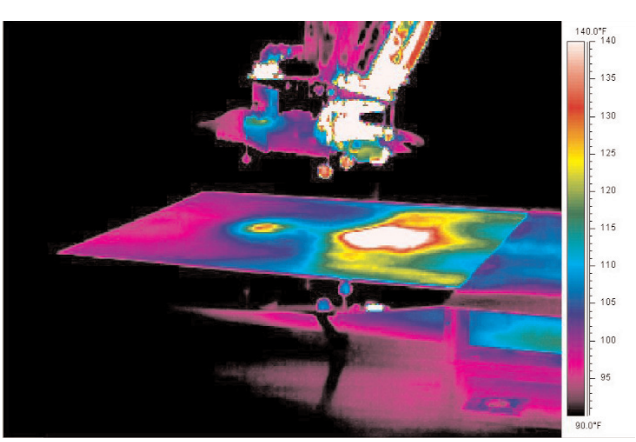


Figure 10. IR image at 0° orientation.

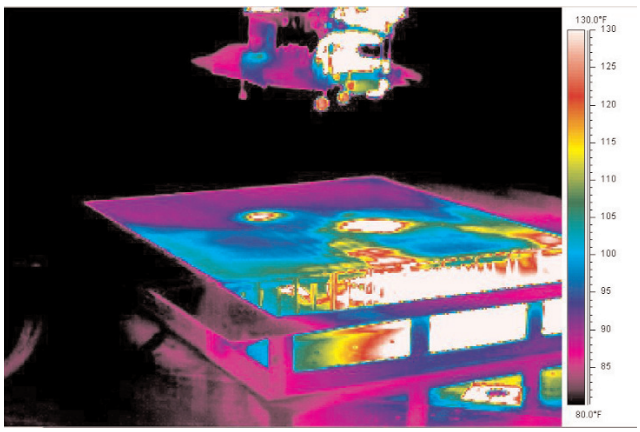


Figure 11. IR image at 45° orientation.

just to the side of the pit. The impingement points of the lift jets can be seen on the surface of the pit. The rear jet is the rather obvious white blob. The turning vanes in the pit deflect all the jet flows aft towards the exhaust section, but some flow still turns forwards when it hits the floor. The blockage of the rear jet within the pit prevents the front jet flow having easy passage to the exhaust section. The front jet flow is forced both sideways and upwards with some of this exiting the pit where it is not wanted. The warm portions along the edges of the pit indicate where the flow is escaping – knowledge of which came from the laser flow visualisation work.

The next picture, Fig. 11, shows a configuration at 45° to the aircraft. This time there is no extension between the pit and the exhaust section.

The flow pattern on the surface of the pit is quite different here. There is obviously less blockage of the front jet flow within the pit. The temperature of the leakage in the back right corner has increased relative to the previous orientation.

Finally, Fig. 12 shows a 90° orientation case. In this case the vanes are angling the flow left relative to the aircraft. There is a noticeable fountain between the front and rear jets and a much hotter leakage at the side of the pit, behind the aircraft.

All the images shown were taken with no wind blowing, and indeed the wind would make very little difference to them. It would, however, make a difference to the behaviour of the leakage flows once they escaped the pit.

Using the measured engine face data and the insights afforded by the smoke and infra-red flow visualisation, the hover pit was modified and adjusted to give best performance over a range of windspeeds and directions. A recommended design was passed on to the test and evaluation team in Fort Worth.

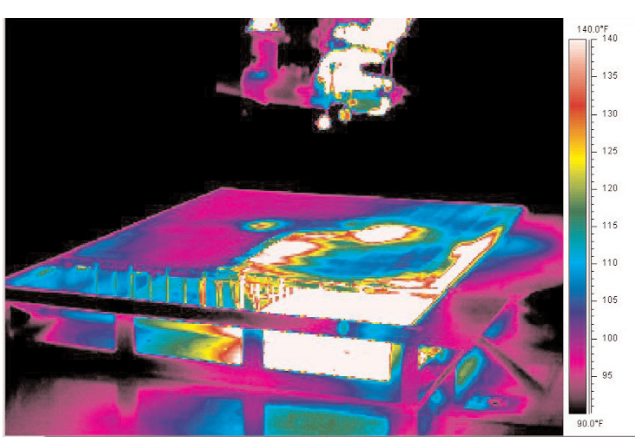


Figure 12. IR image at 90° orientation.

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7.0 PIV INVESTIGATION

The surface oil flow picture shown earlier in the paper indicated some asymmetry in the ground flow patterns, while some of the data taken during testing led the test team to believe there was significant three dimensionality in the fountain flow under the aircraft. It was decided to investigate this further by commissioning a trial using a 3D PIV system.

The FlowMap 3D[9] system was hired in from Dantec Dynamics as a turnkey system, including the laser and associated optics and all the required data logging and analysis software.

7.1 Seeding

Seeding of the jets was always assumed to be difficult. The first problem was whether to test with hot jets or not. At the rear nozzle temperatures required, Dantec recommended that the only feasible seeding material was titanium dioxide powder. Given the nature of the rig and the many bits and pieces within the facility it was felt that this option was unacceptable. Therefore it was decided to test with unheated jets, which permitted the use of olive oil smoke for seeding.

The seeding needed to be introduced far enough upstream of the jet exit that it didn't affect the jet profile. In this instance that meant putting smoke into the nozzle feed upstream of the porous plate used to condition the flow prior to the jet exit. This meant introducing smoke into a high pressure (at least 4Bar) stream, and required a special high pressure smoke generator. Dantec were able to provide one of these, and it was decided to seed the rear nozzle.

Although only one nozzle was explicitly seeded, it was hoped that enough seeding material would be entrained into the general flowfield to adequately characterise what was happening. On the whole, this appeared to be the case, but with reservations noted later.

7.2 Principles of 3D PIV

The basic principles behind both 2D and 3D PIV are fairly straightforward. It is the application of those principles that becomes rather complicated. In the 2D case, a viewing device is set up to look at the seeding particles illuminated by a sheet of laser light. By following these particles over a given period of time their speed and direction, in the plane of the light sheet, can be determined. The method of identifying particles and following them is, of course, very challenging. The approach currently used by Dantec is to use CCD cameras for the viewing devices and to pulse the laser at a very fast rate. For each laser pulse the CCD produces an 'instantaneous' view of all the particles in the view. By comparing two successive views and measuring the distance each particle has travelled it is possible to map the flowfield.

Of course, the clever part is in identifying where each particle in the first image has gone to and where each particle in the second image has come from. Particles appear and disappear at the boundaries of the viewing area and due to cross-plane velocities. Of course, the laser slice does have a finite thickness and provided the time between pulses is short enough then most of the cross-plane velocity should be captured, but not quantified. To get good data requires a high enough concentration of seeding particles and the taking of enough images over a period of time to get a true mean velocity field. If the data rate is sufficiently high then time accurate data can be taken. The Dantec system has built in algorithms to cross-correlate the data being taken, to reject 'rogue' data, and to interrogate and characterise the unsteady aspects of the flowfield.

For the 3D system there are two viewing devices looking at the same viewing window from different angles, and capturing images at the same time. Knowing exactly where each image is viewed from and by comparing the two images taken at the same time, it is possible to resolve the out-of-plane velocities in the data. It is important to get a good wide angle between the two cameras to get the best resolution of these out of plane velocities, with it being preferable for these to make an equal angle either side of the laser sheet.

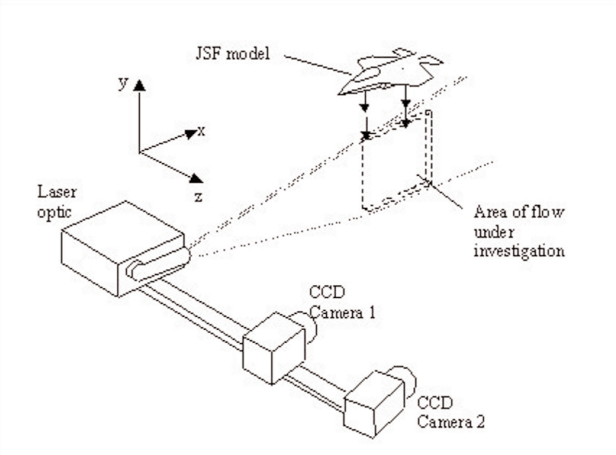


Figure 13. Vertical light sheet arrangement.

Dantec claim that the set-up procedure for the 3D system is not much more onerous than for a 2D system. The chief task is to accurately position and line-up the two cameras.

7.3 GER PIV Set-Up

The area of the flowfield of most interest was beneath the model between the lift jets, but because the active flowfield extends some way from the aircraft, and we did not want to disturb this we were forced to have quite long focal length lenses on the laser and cameras. This in turn meant that with the hardware supplied, i.e. the fixture for supporting the laser and cameras, it was not possible to mount the cameras either side of the laser sheet.

Two different orientations of laser sheet were tested. Initially a vertical light sheet oriented along the axis of the aircraft was tested, as seen in Fig. 13. Reference 10 gives more details.

Following this, a more ambitious horizontal sheet was attempted. The intention was to examine the ground jet flow, including the rear nozzle impingement and the fountain formation. Figure 14 shows a picture of the latter arrangement. Here, the laser is mounted at the bottom, with the light sheet at its minimum possible distance of 31mm off the floor. The two cameras can be seen mounted so that they are focused on the ground beneath the model. The set-up illustrated could not get a good view of the light sheet at lower aircraft heights, due to the wing and fuselage blocking the line of sight.

Because of the angles that the cameras make to the light sheet there is a certain distortion of the view. This is dealt with in the data analysis software provided by Dantec.

Although the set-up of the cameras, getting them both focused on a common target, was claimed to be not much more onerous than a 2D system, it proved much more time consuming than anticipated. Another problem was that to get a good alignment of the laser sheet under the model, with all the safety cut-outs on the equipment, was extremely difficult and time-consuming.

It should be stressed that this was a trial set-up in order to demonstrate the feasibility, or otherwise, of being able to bring in a system at short order to help with flow diagnostics. During the trial it became progressively more difficult to obtain data, and that data became progressively more dubious. It was later realised that this was most likely due to the laser and camera optics becoming contaminated with the seeding material, and with the camera focus wandering over time. In the heat of the moment these aspects were overlooked.

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Figure 14. Horizontal light sheet set-up.

7.4 GER PIV Data

The earlier data taken were by far the most convincing, this being with the vertical laser sheet. Three constant aircraft heights were investigated at three different lateral positions. The heights were 10, 15 and 20ft full scale (undercarriage height), and the positions were on the aircraft centreline, on the centreline of the main intake and on the centreline of the roll jet. Figure 15 shows data from the centreline position with the aircraft at 20ft. The 3D viewing window for the PIV system is about 9ft high at full scale. This is the 2D data, with the two views from the cameras overlaid on each other, and plotted using Amtec Tecplot. Although Dantec supplied data plotting software, they were aware that it had limitations and recommended the use of specialist plotting software. Our experience confirmed this view.

Each plot is the mean of at least 50 datasets, although this number was varied during the trial. This is really too little to get highly accurate mean values, by at least an order of magnitude, but it was considered that it should be sufficient to demonstrate whether the system was capturing the essence of the data.

Figure 15 plots contours of vertical velocity overlaid with streamlines computed by Tecplot. The streamlines indicate the speed of the flow by the length of the dash, the longer the faster. The rear jet is visible at $x = 200$ and the front jet is at $x = -400$. Although the front jet data looks a bit patchy it should be remembered that there is no seeding in this jet; it is merely entraining seeding particles from the surroundings. The fountain flow can be seen to be roughly mid-way between the two lift jets and inclined slightly aft.

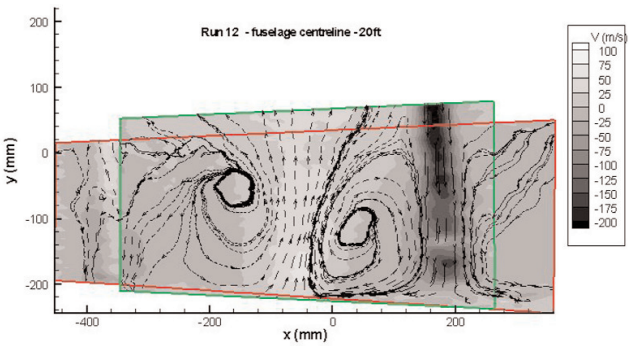


Figure 15. Centreline – aircraft at 20ft (2D).

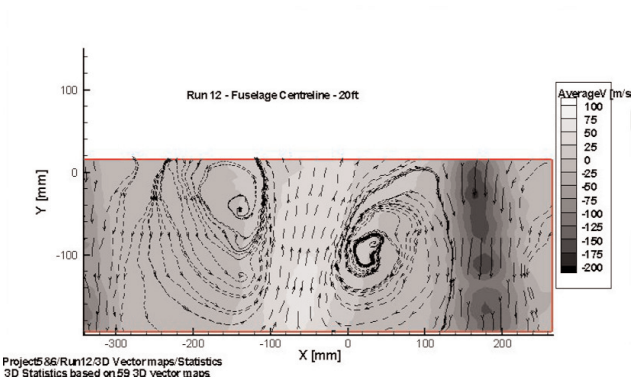


Figure 16. Centreline – aircraft at 20ft – vertical velocity contours (3D).

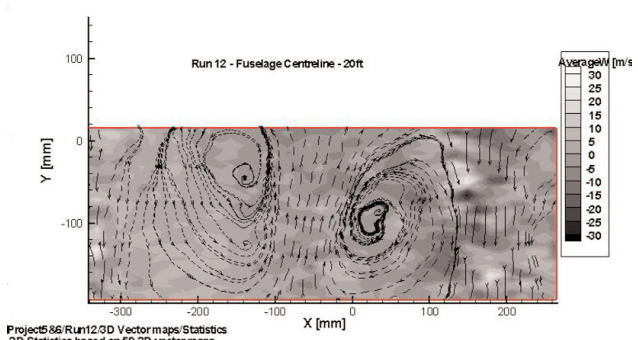


Figure 17. Centreline – aircraft at 20ft – cross-flow velocity contours (3D).

The PIV 3D computation can obviously only take place where the two camera views overlap. Figure 16 shows the 3D computation for the same data as Fig. 15, and with the same plot parameters. Although there are detailed differences, the flow looks substantially the same. Figure 17 shows a plot of the cross-flow velocity, w, for this data. Negative w is coming out of the page and positive w is going into the page. Being on the centreline it would be expected that there should be minimal cross-flows, and so it proves.

The data on the centreline from the three hover heights looked very similar, but this was not the case at the plane of the aircraft intakes, which is between the centreline and the roll jets. The following

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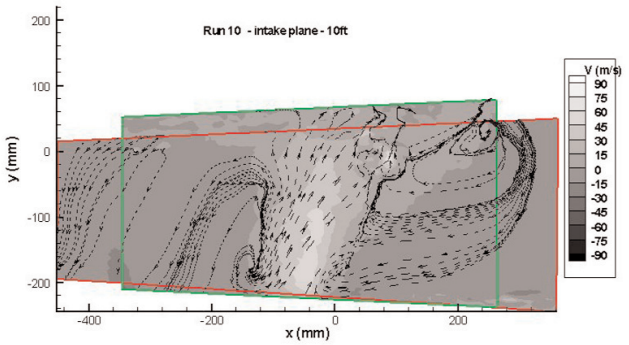


Figure 18. Intake plane – aircraft at 10ft (2D).

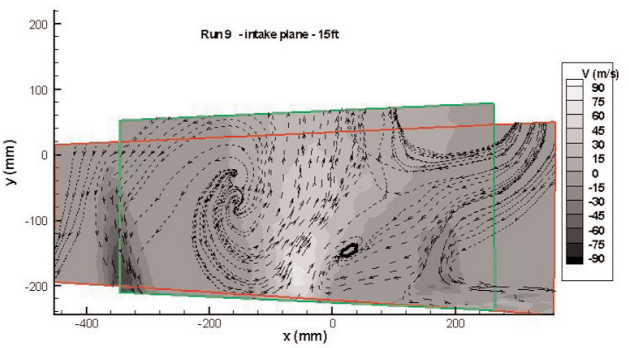


Figure 19. Intake plane – aircraft at 15ft (2D).

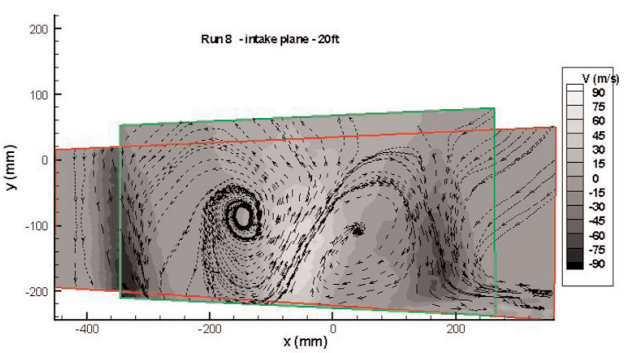


Figure 20. Intake plane – Aircraft at 20ft (2D).

sequence of plots shows the 2D data plotted in the same way as before. At higher aircraft heights the spreading main jets can be seen entering the viewing window at the front and back of the view. It can be seen quite clearly that the upper portion of the fountain is inclined aft at 10ft, is nearly vertical at 15ft and is inclined forward at 20ft. This ties in very well with the ingestion data, which tended to show ingestion occurring at about 20ft with this configuration, but decreasing at lower heights. Comparing the centreline and intake plane measurements, Figure 15 and Fig. 20, it is clear there is a strong three dimensional element to the flowfield.

The PIV 3D data ought to have shed more light on the three dimensionality of the flow but, for whatever reason, the system really struggled to provide believable data. Figure 21 shows the 3D version of Fig. 19. This completely different flowfield is the most extreme example, and is obviously wrong, but the other heights had sufficient differences to question their validity.

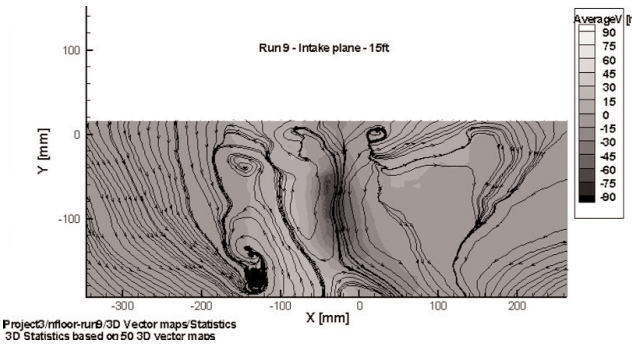


Figure 21. Intake Plane – aircraft at 15ft (3D).

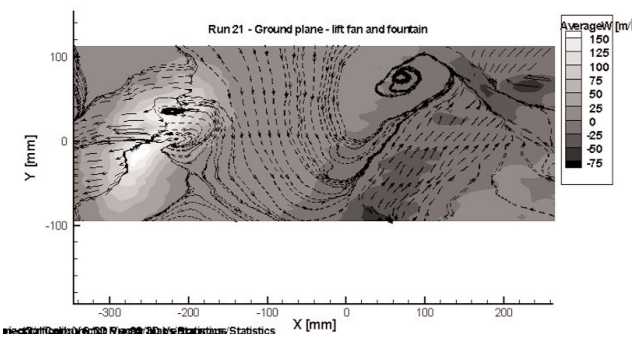


Figure 22. Horizontal slice near the ground – cross-flow velocity contours (3D).

The most likely explanation for this is that the seeding rate was not really sufficient to capture the flow. Having a second seeding device in the front nozzle would undoubtedly have helped in this regard.

For the horizontal laser sheet the great difficulty was in getting the laser close enough to the floor to capture enough of the ground jet, particularly where the intention was to characterise the rear jet behaviour. Figure 22 shows data from the most successful set-up achieved. Here the aircraft was at 20ft and the laser was at 45° to the aircraft axis; so the aircraft nose would be pointing to the top left (NorthWest) as viewed. It is possible to see the front jet impingement and a portion of the fountain to the right of the centreline. Positive values of W are going into the page and negative are coming out of the page.

The rather odd behaviour of the fountain flow in the top right corner of the plot appears to be showing the influence of the roll jet. Thus, the strength of the up-flow in the fountain, which was decreasing away from the centreline, suddenly increases. The outwash indicated by the streamlines in the fountain also abruptly stops. Considerable care is needed in interpreting the streamline data as they are produced by a 2D computation in a highly 3D flowfield. Nevertheless, it is likely that the constraining influence of the roll jet helps to produce the forward inclination of the fountain at the intake plane. The amount of information on this plot can be compared with the oil flow picture in Fig. 5, which shows the same area of interest.

Overall, the PIV trial showed a mixed bag of positives and negatives. The hardware was relatively straightforward to set-up, although the alignment and focus of the cameras needed a lot of fiddling to get right. This would probably be improved with practice. Setting up the hardware for vertical light slices was much easier than doing it for horizontal ones, with the additional problem of getting the laser sheet close enough to the ground.

The seeding hardware worked well, and gave acceptable data rates for 2D PIV with very little tweaking. The data rates were not really

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good enough for the 3D system to work reliably. Although adding a second seeding source would have improved things it is not clear if that would have been enough.

The quality of data allowed a more detailed insight into the jet and fountain flow than any other diagnostic previously used, although the majority of this was from the 2D data.

Overall, to support HGI testing for an aircraft programme, the ability to quickly use a 2D PIV system would be a distinct benefit. At present, the extra time and complexity of setting up a 3D system would not be worthwhile.

8.0 CONCLUSIONS

The paper has described the BAE Systems Ground Effects Rig and it's principal instrumentation – an engine face thermocouple rake, measuring the engine inlet temperature. Although giving an accurate measure of temperature, this data gives no indication of the flow phenomena leading to the temperature rise. A range of flow diagnostic techniques has been described which help the design team build a picture of the very three-dimensional flowfield around the aircraft, and thus enable improvements to be incorporated into the design.

Simple and cheap diagnostic techniques, such as flow-tufting, can give a good insight into the flowfield, but sometimes more advanced techniques are required. Laser flow visualisation and infra-red imaging can be set up quite easily. 2D PIV seems reasonably straightforward, and robust enough for project work, but 3D PIV, at the moment, is a step too far in terms of complexity and overall pay-back.

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