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May 1990

In-Flight Measurements on a Tornado Aircraft
for Stores Carriage and Release Research

by

Dr. G. W. Foster

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IN-FLIGHT MEASUREMENTS ON A TORNADO AIRCRAFT FOR STORES CARRIAGE AND RELEASE RESEARCH

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IN-FLIGHT MEASUREMENTS ON A TORNADO AIRCRAFT FOR STORES CARRIAGE AND RELEASE RESEARCH

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SUMMARY

Flight trials with a Tornado aircraft to produce full-scale experimental data for stores carriage loads, release trajectories and flow surveys are described. The instrumentation carried by the aircraft is introduced and the facilities for analysing the resulting data outlined. Some examples from flow surveys are presented.

1 INTRODUCTION

Tornado ZA326 (fig.1), which is based at RAE Bedford, is performing a series of flight experiments to investigate several aspects of stores carriage and release aerodynamics. The major aim of the programme is to provide a set of high quality, full-scale experimental data which can be used to compare and validate predictive techniques such as wind tunnel observations and computational fluid dynamics. The programme is not concerned with the clearance of particular stores to be carried on Tornado; the airframe used is just a convenient carrier and the stores employed have been based on the BL755 bomb. One notable feature of the Tornado is that being a swing-wing aircraft it can provide a wider range of test cases. The aircraft is capable of supersonic flight which means that the transonic regime, a difficult area for predictive techniques but one likely to be important for future aircraft, is accessible.

The flight tests have three elements :

1. The measurement of the loads experienced by stores during carriage using special stores which are instrumented with internal balances to observe forces and moments.

2. The filming of store releases from the under fuselage pylons by high-speed cine cameras mounted outboard on the wings and under the aircraft's forward fuselage.

3. The measurement of the flow field in the region below pylons where stores are carried and through which stores pass immediately after release.

Items 1 and 2 are described in detail in ref.1 while a description of item 3, the flow-survey work, forms the second part of this paper. The first part of the paper outlines the facilities available on Tornado ZA326 such as the instrumentation and data recording systems. The facilities for data replay and analysis are also covered.

2 DATA CAPTURE AND REPLAY

2.1 Aircraft facilities

Tornado ZA326 is a general purpose experimental aircraft employed on a range of tasks for a variety of users both within and external to the RAE. To perform this wide range of trials the aircraft has been extensively instrumented and has MODAS (Modular Data Acquisition System) recording for data capture. Among the instrumentation which is of interest during the stores aerodynamics programme are :

1. position transducers on all the aircraft control surfaces,

2. a set of accelerometers and rate gyroscopes near the aircraft centre-of-gravity, as well as the aircraft's inertial navigation system,

3. the fuel state (so the aircraft's mass is known),

4. the aircraft's air data system,

5. an additional air data system based on a pair of 5-hole conical yawmeters.

The MODAS equipment consists of a small number of Acquisition Units into which the many analogue, digital and discrete (on/off) signals from instruments or aircraft systems are fed. These condition the signals (if required), sample and, where necessary, digitise the data, and pass the information when requested to the Processing Unit. This samples the channels available in the various Acquisition Units according to a scan pattern held in memory, actually in an PROM. Upto 8 different patterns can be held and may be selected in flight by the pilots to suit different tasks. The resulting multiplexed data stream is fed to a rugged, digital, 1" magnetic tape recorder. The system on the Tornado is capable of recording upto 128K 12-bit samples per second with extensive data checking and correction. Facilities are provided in both the Acquisition Units and the ground replay (see below) to allow data channels which require more than 12 bit resolution to be split over several 12-bit 'words' and latter recombined. Other supporting information (such as the aircraft identity, the time and the scan pattern in use) is also recorded to ease identifying and replaying the data. A small Control Unit in the cockpit allows the pilot to initiate recordings, switch scan patterns and so on.

Special wiring has been installed in the airframe to bring signals from, for example, control surfaces and pylons to the Acquisition Units. In a few cases other approaches have had to be adopted. The running of the cameras on the outer wing pylons during stores releases was initiated by radio from the aircraft to the camera controllers so as to avoid wiring to these outboard pylons. The instrumented stores used for the carriage loads trials are designed for use on a variety of aircraft and so have internal data recorders. However, control lines and an event channel to be recorded on both MODAS and the stores internal recorders (to allow synchronisation) were still needed.

Data from the aircraft's air data and inertial navigation systems can be acquired and recorded amongst the MODAS data. Furthermore, it is possible to take data from the Tornado's main computer and record this on MODAS.

2.2 Air data systems

Establishing the flight conditions during the stores aerodynamics flight trials is an important consideration when comparisons against predictive techniques are going to be attempted. Acquiring this information tends to highlight one of the problems of flight testing when compared with wind tunnel testing where accurate measurement and repeatability of conditions can easily be achieved. In flight they tend to be much more elusive.

The standard Tornado air data system gave information on pressure altitude, air density, Mach number, true airspeed and total temperature. A 'true angle of attack' is also available from this source; this is based on the readings of a pair of Ferranti Airflow Direction Detectors on either side of the fuselage. These are nulling devices which rotate to equalise the pressure at two slots in the surface of a tapered cylinder projecting out from the aircraft skin. When the pressure difference has been nulled they are taken to be pointing into the local airflow. A 'position error correction' (based on flight tests performed during Tornado development) is applied to the sensed rotation within the air data system on the aircraft to yield the 'true angle of attack' of the airframe. Unfortunately no corresponding sideslip sensor is fitted.

As part of a programme to explore and develop advanced multi-function air data sensors, two 5-hole conical yawmeters have been mounted on ZA326. These are on small outriggers just behind the nose radome on either side of the fuselage fig.2 but considerably above the centre line. Each yawmeter consists of a truncated cone (semi-apex angle 30 degrees) with a cylindrical afterbody. There are holes on the forward facing surface and at 90 degree intervals around the conical surface. These holes are piped back to pressure transducers just inside the aircraft skin and the ten pressures (five for each head) may be recorded on MODAS. These are not nulling devices and so the recorded pressures are processed on the ground (using a calibration based on wind tunnel results) to give the local flow direction (and Mach number, if required) at each of the heads. Using the known geometric alignment of the two heads the flow direction can be obtained in the aircraft axis system and the results from the two averaged. The resulting flow direction angles are named ALPHA5 and BETA5. These require further 'position error corrections' so as to yield the direction of the airflow approaching the airframe and flight tests have been performed to find these.

A series of steady horizontal runs where performed in calm air. The aircraft's longitudinal accelerometer can then in effect be used as a pendulum to give pitch attitude and, provided the flight path is horizontal, this is the angle of attack. Fig.3 shows the results of these runs. Here 'calculated' are the values from the longitudinal accelerometer. The results are more scattered than one might have wished but the line shown has been fitted to the points, and using this line allows a corrected value, ALPHA5C, to be derived from ALPHA5.

A corresponding correction is needed for BETA5, but is somewhat more complicated to obtain as the gravity vector no longer provides a useful reference direction. However, by recording the aircraft's accelerations and angular rates during a manoeuvre in calm air, for example entry into a sideslip or a dutch roll oscillation, it is possible by integrating the kinematic equations of motion to deduce the time history of the variation in sideslip angle during the manoeuvre. The side-wash correction factor

can then be estimated by scaling BETA5 to give a best match to the
kinematically derived sideslip. This process has been peformed (upto now)
for manoeuvres at a (limited) range of flight conditions. The results tend
to indicate that BETA5 over-reads the true sideslip by about 4% at low
incidence but changes more or less linearly to under-reading by 6% at an
ALPHA5 of 11.5 degrees. A fitted line has thus been used to give a
side-wash correction factor which varies with ALPHA5.

The kinematic compatibility method outlined above could equally be used,
with suitable manoeuvres, to estimate the up-wash correction factor for the
incidence sensors but this has not been pursued in depth. The few results
obtained tend to agree with the slope of the line in fig.3. One remaining
problem is that the kinematic compatibility method effectively deals in
perturbations during a manoeuvre and so can not give very good information
concerning offsets or biases. It was noticed that in many of the runs
where the pilot claimed to have established zero sideslip conditions,
BETA5C was not zero but tended to be negative and out to -0.5 degrees. To
investigate this, the mean BETA5C during a series of steady runs at low
sideslip was compared to the mean lateral acceleration (divided by the
dynamic pressure) for the runs. This showed that non-zero BETA5C values
are associated with non-zero lateral accelerations. There was extremely
good correlation, and any bias in BETA5C is certainly less than 0.1 degree.

Returning to the measurement of angle of attack, a comparison of the mean
ALPHA5C against the mean 'true angle of attack' from the air data system
during a set of steady runs with little sideslip showed that most of the
discrepancy between them was explained by a 0.53 degree offset between the
instruments. If we define ALPHA5D to be ALPHA5C plus this offset, then
ALPHA5D and 'true angle of attack' agree well when the sideslip is low. Of
course one could equally claim the error lies in 'true angle of attack' and
apply the opposite offset to yield a "corrected" 'true angle of attack',
indeed evidence from the flight trials which led to fig.3 tend to show
there may be such a bias error. Evenso, for the remainder of this paper
ALPHA5D will be presented.

There are two reasons for wishing to present an incidence which is derived
from the 5-hole heads for the present application. The first is for
compatibility of data source with the BETA5C from the heads, the second and
much more important reason is that 'true angle of attack' appears to be
influenced by sideslip whereas ALPHA5 (and those derived from it) are
nearly insensitive to sideslip. Fig.4 gives an example of this. 'True
angle of attack' from the aircraft's air data system is here labelled
IADTATT. Since runs with the aircraft sideslipping were part of the stores
aerodynamics flight trials programme, particularly the flow-survey part,
relying on IADTATT seems unwise.

2.3 Ground replay and analysis

Ground replay of MODAS flight tapes takes place on a PDP11/70 computer
which has suitable 1" magnetic tape decks and software, and is dedicated to
this task. Replay systems are available at RAE Bedford, RAE Farnborough
and a number of other sites within the UK where MODAS is used. Amongst the
facilities provided by the ground replay (ref.2) are :

1. A directory summarising the contents of an airborne tape can be produced giving for example the start and end times of the recorder runs found.

2. Time history plots can be produced on an electrostatic plotter. Several channels can be plotted in parallel, and if required calibrations can be applied so the axes are in engineering units rather than just raw 'counts' as recorded on the digital tape.

3. Edit sequences, defined by a choice of time slice and a choice of channels, can be transferred to a half inch computer compatible tape (CCT). This is the form in which data is produced for transfer to other computers for further analysis.

4. Means of maintaining information about flight tapes, edit sequence definitions and instrument calibrations (and their periods of applicability) are provided.

All the MODAS data from the stores aerodynamics programme is replayed to produce a CCT. However, the subsequent analysis employs two different routes. The data from the carriage loads and store release flights is transferred to RAE Farnborough and uses specially written software (ref.3) on the RAE central Multics computer. The data from the flow-survey flights is handled using the system available on the VAX computers at RAE Bedford. This system is employed by most of the users of aircraft fitted with MODAS at Bedford and is described in ref.4. After the MODAS recording and replay to CCT the main components of the system are :

1. DATS, a time series analysis package

2. Ingres, a relational database

3. MANS (MODAS Analysis System), which provides the means for transferring data from a MODAS CCT into DATS and Ingres

It should be noted that 1. and 2. are commercial packages, as is MODAS, and only 3. is specially written software.

3 IN-FLIGHT FLOW-SURVEY PROGRAMME

3.1 Background

One of the deficiencies of the carriage loads and release trajectory data is that if a prediction technique does not perform satisfactorily (when compared against such data) then there can be (at least) two sources for the error. First, the flow field around the aircraft which the store experiences may have been predicted wrongly , or second, the behaviour of the store in that flow field, particularly the forces experienced, may be incorrect. In an attempt to separate these two effects direct measurements of the flow speed and direction in the region below pylons are being made on the Tornado. Two flow-survey rigs have been manufactured and have commenced flight testing.

3.2 Traversing rig

This rig, fig.5, carries two five-hole conical yawmeters on an arm which can traverse backwards and forwards by 2.47 metres. As the carriage traverses the arm swings from side to side through ±50 degrees so that the flow conditions are in effect measured along zig-zag paths on two semi-cylinders. Ideally one would have liked a device in which the position of a sensing head could be varied independently in all three axes, but to withstand the rigours of flight this design was accepted. Evenso the rig is mechanically complex and electrical connections are problematical. The traversing mechanism is powered by electric motors mounted at the rear of the fixed part of the rig which drive a lead screw. A spigot follows a serpentine slot in the base plate of the track to control the swinging of the arm. A single traverse takes about one minute.

The yawmeters are similar in outline to those mounted on the aircraft and discussed above, but they do not have holes in the surface which are piped back to pressure transducers. Instead the pressure transducers are recessed into the surface of the device and each is protected by a perforated metal screen. This produces a compact, self-contained device (well suited to mounting in the confines of the swinging arm) with a very high rate of response, over 200 Hz. The latter characteristic means that if during a traverse a head should pass through a region where the flow conditions are changing rapidly the data gathered will not be distorted by the response characteristics of the device. Ref.5 describes these fast response air data sensors in detail.

It will be clear from fig.5 that the supporting, fixed part of the rig is quite large and intrusive. We do not believe that it is possible or worthwhile to 'calibrate-out' the effect of this on the measured flow fields. A better approach is to include the rig as as part of the fixed structure when predicting the flow which the probes will encounter. Mathematical models of the traversing rig suitable for use in flow prediction codes have already been produced.

The rig has been flown as part of the flight clearance procedure. Unfortunately during this the ribbon cable which carries power to, and data from, the traversing carriage became detached. The rig is now being modified to enclose the ribbon cable, and as yet no flow data has been gathered.

3.3 Fixed rig - description

In this flow-survey rig, fig.6, there are eight conical yawmeters heads arranged in a cruciform configuration. These are half-size versions of those mounted on the aircraft fuselage. The position of the cruciform is fixed during flight but can be moved between seven longitudinal stations on the carriage when on the ground. The carriage is much more compact and is little more than an extension to the pylon. A ninth sensor head projects from the forward end of the carriage. The heads used are of the piped design and the 45 pressures are measured by a single Scanivalve at the base of the cruciform.

A short initial period of flying with this rig took place in Autumn 1989. Four flights were performed to provide clearance for the rig on the under-fuselage pylons. Four data gathering flights were then carried out.

Considerable further flying is planned for the summer of 1990 when the aircraft returns to service after a major inspection.

3.4 Fixed rig - flight measurements

Fig.7 shows a typical recording during a single recorder run from one of the data gathering flights, flight 548. The top trace shows the time history from the pressure transducer attached to the Scanivalve which cycles round the 45 pressures from the nine 5-hole heads on the rig. The transducer is sampled at 256 samples per second and this sampling is not synchronised with the Scanivalve movement in any way. The pilot switched on the MODAS recorder and established steady horizontal, straight ahead flight at a Mach number very near 0.8 . In fact sideslip was slightly negative although he was aiming for zero sideslip conditions. He then pressed the control button to initiate a scan by the Scanivalve. When the Scanivalve is not in motion the pressure at FRDIFF is from the front hole of the forward head, but once scanning commences it varies as each port is scanned. This scan is labelled A on fig.7. A second scan (B) was made immediately after. Fig.8 shows FRDIFF in greater detail for scan A and the start of scan B. It also shows the recording of FPABS which is an absolute pressure transducer measuring the backing pressure being applied to the differential transducer FRDIFF; this is gradually decreasing during these two scans. The backing pressure comes from an enclosed volume in the rig which is connected to static holes on the side of the rig through 'laggy' pipework. Using a high resolution differential transducer to compare the pressure at each hole on a yawmeter against a backing pressure (which varies only slowly) increases the accuracy of the flow parameters as these tend to depend on differences in pressure between the various holes.

Returning to fig.7 the pilot entered a steady negative sideslip and took two scans (C and D), then a positive sideslip for two more (E and F). Finally a steady horizontal 2g turn was set up and two further scans (G and H) taken at the resulting increased incidence.

Computer software has been produced which processes the type of records shown here. Each individual scan is identified and the mean flight conditions and aircraft control surface positions during the scan are stored in an Ingres relational database. The software goes on to extract the pressure levels at each of the heads on the rig from the FRDIFF time history. This is a far from trivial problem due to the lack of synchronisation and the variation in the dwell time at each port even during a single scan. These pressures are processed (using the same formulae based on wind tunnel tests as the fuselage mounted heads) to give flow Mach number and direction. Using the known geometric orientation of the heads to the aircraft axis system the flow direction is then transformed to aircraft axes. The Mach number and direction at each of the 9 heads is stored in the relational database. The process is repeated for each of the 8 scans in this record.

Fig.9 shows the measured flow conditions at the fixed rig and for the airframe during run R07 scan A of flight 548. The 8 lower heads are on the cruciform, the one directly above them is the head projecting forward of the rig carriage, while the aircraft flight conditions are shown in the top right corner. The arrows can be thought of as fixed-length tufts which have aligned themselves with the flow direction. The view is looking backwards onto the front of the cruciform and so each of the arrows is in

fact pointing away. The radius of the solid circles show the flow Mach
number at each head while the dashed circles show the aircraft Mach number
(IADMACH) for comparison. The actual value of IADMACH in this case is
0.804 as shown. The flow speed at all the nine heads on the rig is less
than IADMACH. The aircraft's incidence (3.88 degrees) and sideslip (-0.32
degrees) are shown beside the arrow pointing in this direction. The small
solid inner circle shows where the arrow head would lie if the incidence
magnitude were 1 degree. The downflow increases as we move away from the
under side of the aircraft. The outflow apparent from the results along
the cross-bar of the cruciform may arise from the flow around the pylon and
the fixed-rig's carriage. It is possible that the flow direction shown for
the cruciform may be influenced by interference between the 8 heads and
their supporting structure. Wind tunnel tests on the cruciform in
isolation are in hand to investigate this and may lead to further
corrections.

Fig.10 shows a similar diagram for scan C from the same flight and run with
the aircraft now in a steady sideslip of -3.13 degrees.

The position of the rig and cruciform for the data gathering flights is
shown in fig.11, while the range of aircraft Mach number (IADMACH) and
incidence (ALPHA5D) covered by the scans where aircraft sideslip was low in
three of the flights is shown in fig.12. The absolute value of BETA5C was
less than 1 degree for all these 143 scans, in fact it was less than
0.5 degrees in all but three scans. The fourth flight, 549, with the rig
in the rearmost position has not been included as it was found that much of
the cruciform of heads was then within a region of turbulent flow. Some of
the flight conditions in flight 550 (with the rig on the middle pylon of
the under fuselage shoulder and the cruciform in the mid position of the
rig) also showed evidence of turbulence particularly at the forward head.

The subsonic points in fig.12 form three bands across the plot. The lower
band comes from runs at 5000 feet altitude in 1g flight with the incidence
required decreasing as the Mach number increases. The second band has two
sources. First are the 1g runs at 20,000 feet. The decreased air density
means that for the same Mach number a greater incidence in needed than at
the lower altitude. In fact the coefficient of lift has to increase by a
factor of 1.8 . Secondly there are runs at 5000 feet in 2g turns; in this
case of course the coefficient of lift has to increase by a factor of 2.
As this is close to 1.8 the two conditions require very similar incidences.
The third, upper band are the 2g turns at 20000 feet. Supersonically the
same pattern can just about be seen.

Looking first at the lower band (1g flight at 5000 feet), ideally one would
have hoped for groups of 6 points very close together; two scans in each of
the three flights. There are some close approximations to this but with
some missing and some outlying points. For the purposes of making
comparisons between flow prediction techniques and the flow measurements
made by the rig it seems economic to make predictions at the mean flight
conditions for a group of closely clustered points and compare this with
the flight measured flows for the cruciform positions covered by the flight
points.

Five such groups or classes have been picked out on fig.12. Classes 0, 2
and 3 correspond to the flight conditions used for the store release
flights and were also covered in the carriage loads flights. Unfortunately
class 0 is somewhat spread out because for the early runs during one of the

flow-survey flights the pilot used the head-down Machmeter rather than the head-up display of Mach number. The head-down one is a pneumatic device which is not as fully corrected as that from the Tornado air data system which is displayed head-up. The net result was that IADMACH was well below 0.5 and incidence increased. It was therefore decided to include class 1, at Mach 0.6, which gives a better set of data.

The flows measured at the 6 scans in class 1 are shown in fig.13. The pairs of scans come from the immediate repeats performed by the pilot. So, for example, the top pair come from R13A and R13B of flight 548. In all three flights these measured flows shows good repeatability within the pairs. Moving down the page the cruciform is moving further aft along the under fuselage shoulder pylon. As a further check on repeatability, we can note that the rig was mounted on the same forward pylon for flights 548 (top pair) and 553 (centre pair) and so the forward head (plotted here directly above the cruciform) is in the same position for these two flights. The measured flow at this point is very similar between the two flights but changes (showing more incidence and less sideslip) when the rig is moved back to the middle pylon for flight 550.

4 CONCLUSIONS

Flight trials on Tornado ZA326 are providing high-quality full-scale data on the aerodynamics of stores during carriage and release. The aircraft and store instrumentation has been proved and, where necessary, calibrated in flight. Flow fields below pylons are being measured using a specially constructed rig and a small sample of the flow-survey data has been given. Analysis and reduction of the data recorded is producing results against which predictive techniques, such as wind tunnel and computational fluid dynamics may be assessed.

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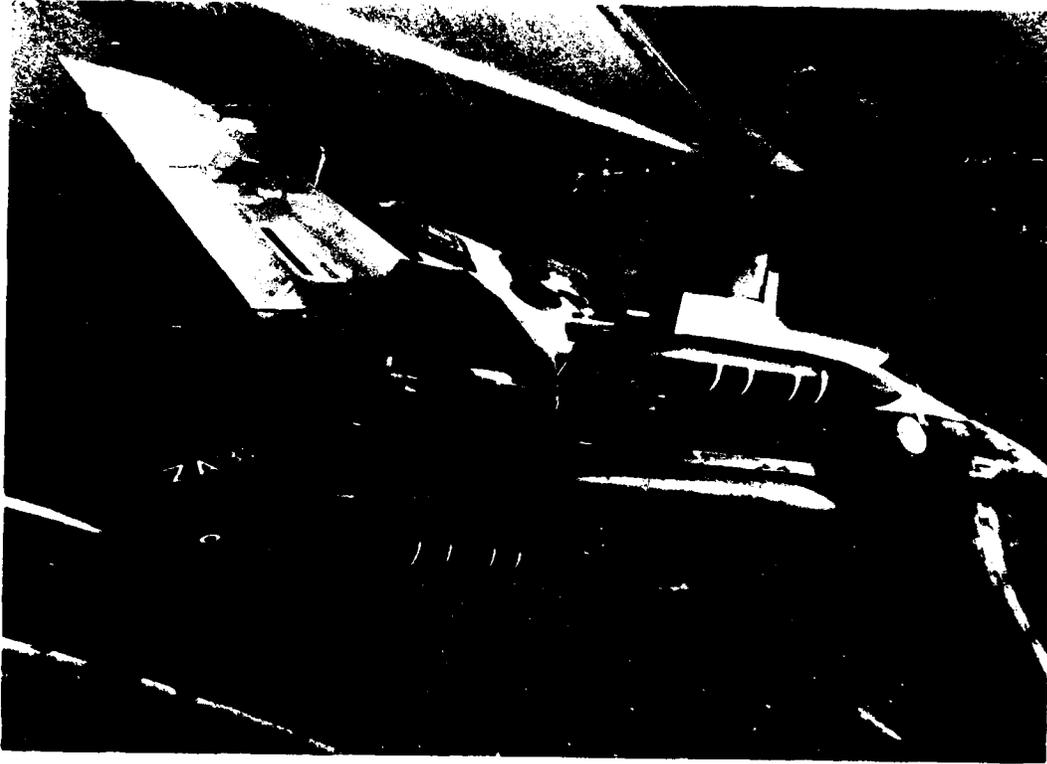
Fig 1 Tornado ZA326

Fig 2 Conical yawmeter mounted on aircraft fuselage

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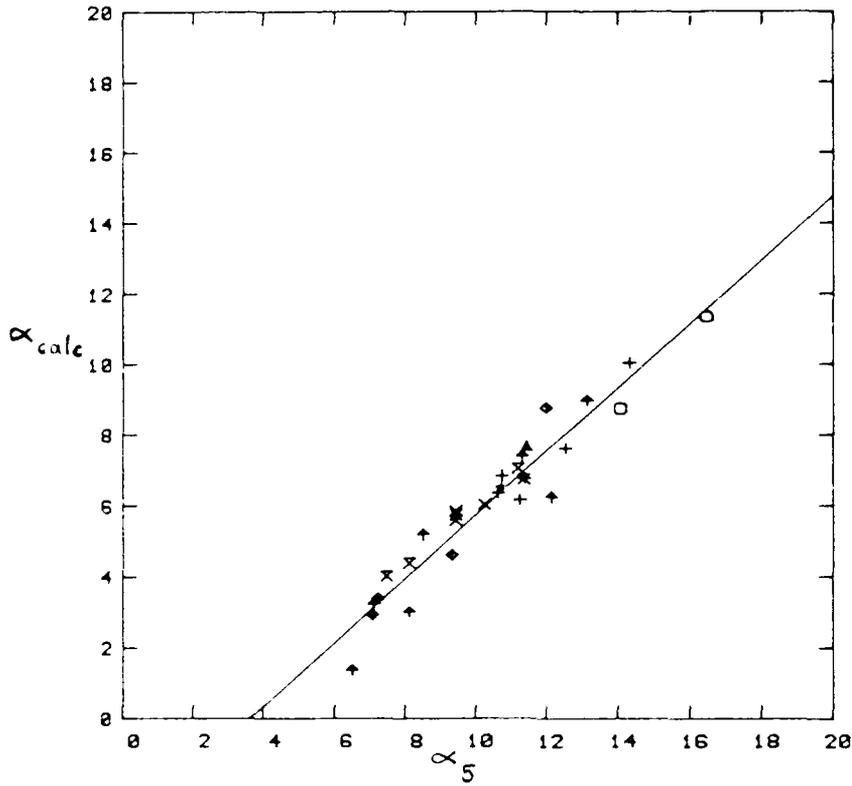
Fig 3 In-flight calibration of ALPHA5
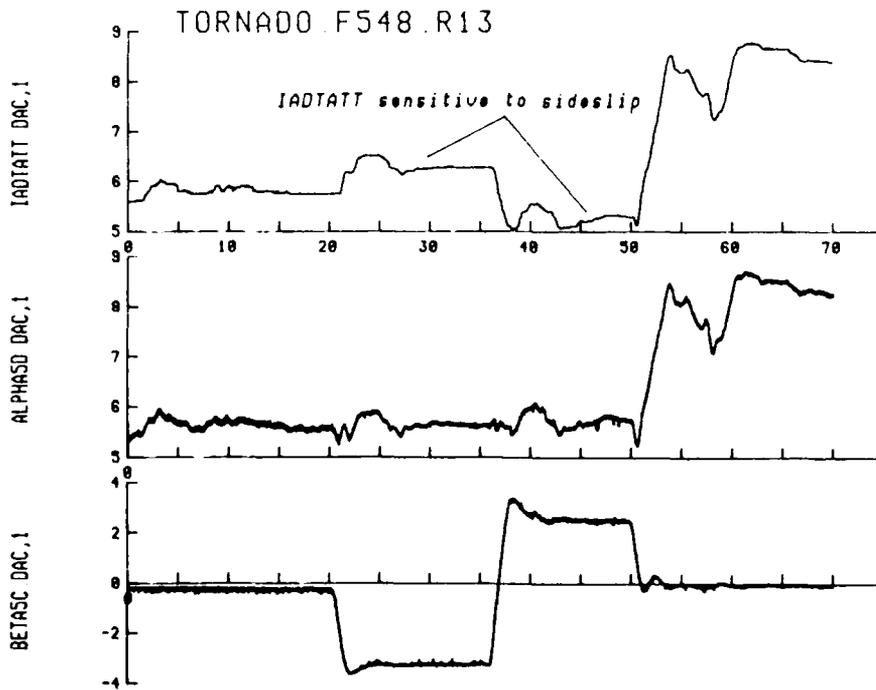

Fig 4 Sensitivity of angle of attack measurements to sideslip

WING

INBOARD
PYLON

LEAD-SCREW

INSTRUMENTATION
PACK

FORWARD

RIBBON CABLE

RAKE

FT

SENSOR HEADS

ROLL
RIGHT

ROLL
LEFT

MOTORS
(2 × 17 AMP)

AIRFLOW PRESSURES AROUND
THE CONICAL HEAD ARE MEASURED
AT THE 5 PORTS SHOWN
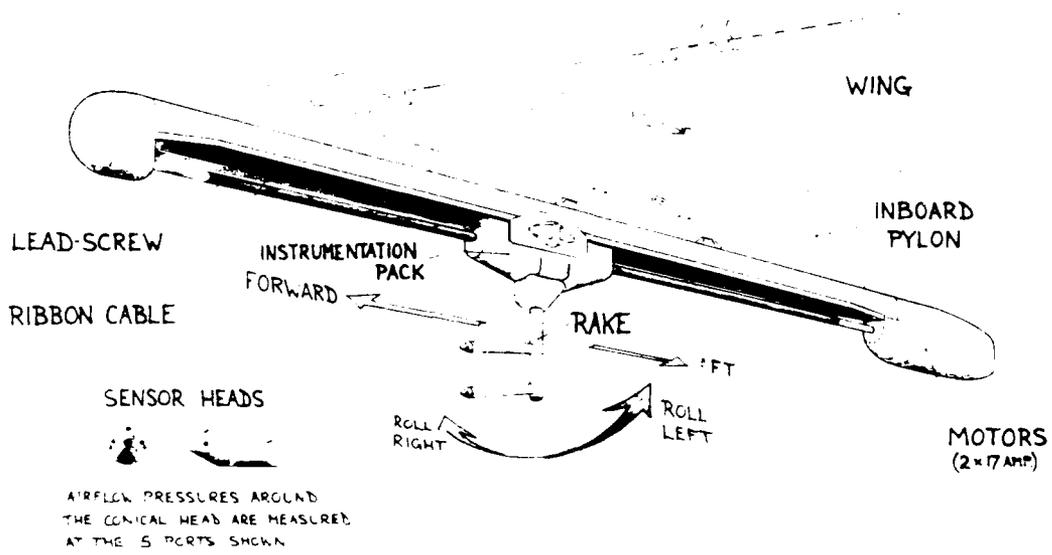
Fig 5 Traversing flow-survey rig
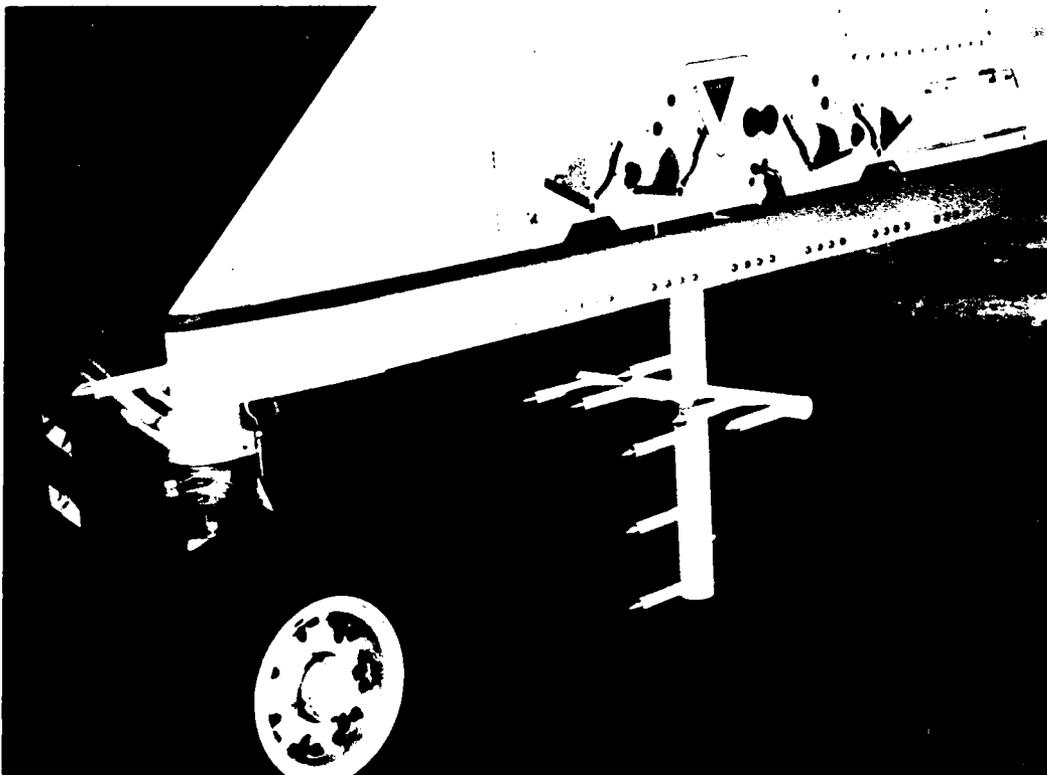
Fig 6 Fixed flow-survey rig
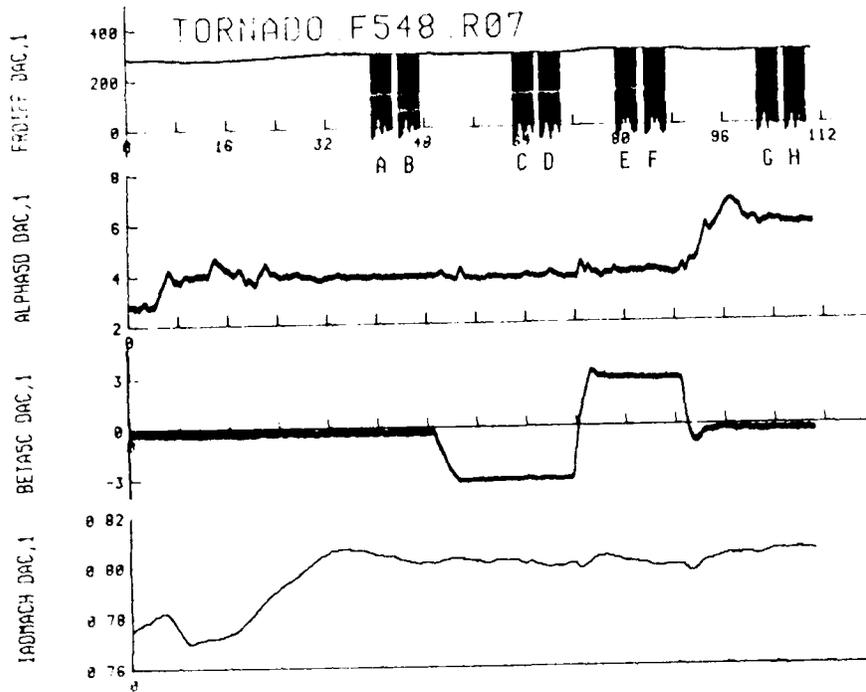
Fig 7 Example of data recorded with fixed rig
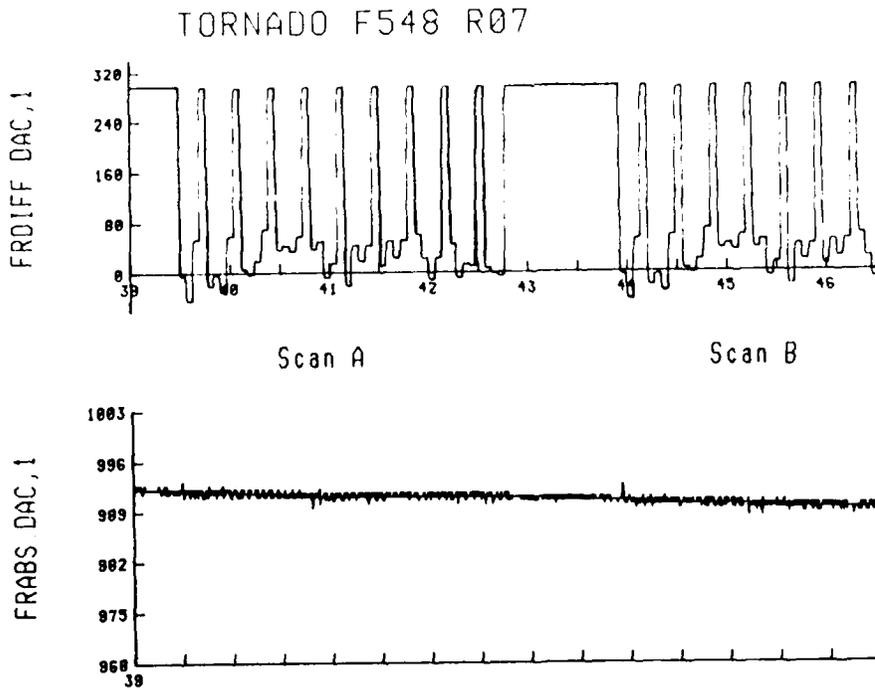
Fig 8 Detail of data recorded with fixed rig
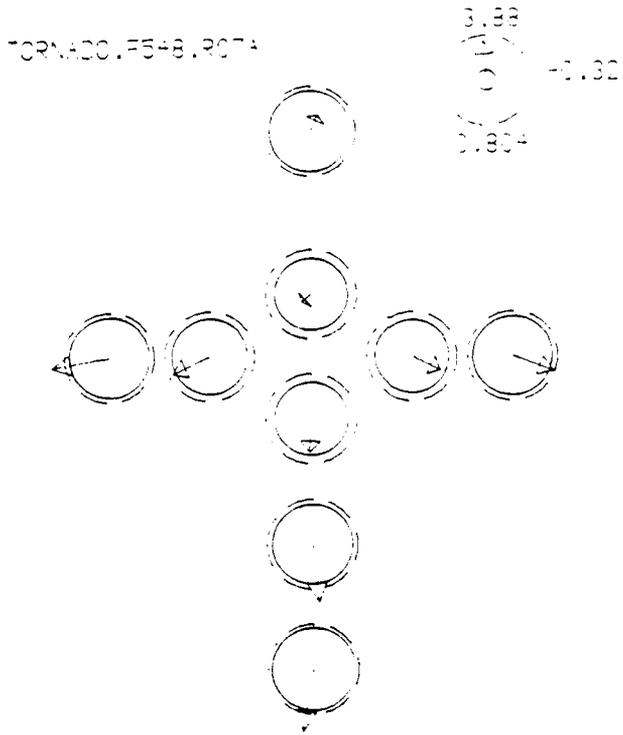
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Fig 9 Example of flow survey results from fixed rig
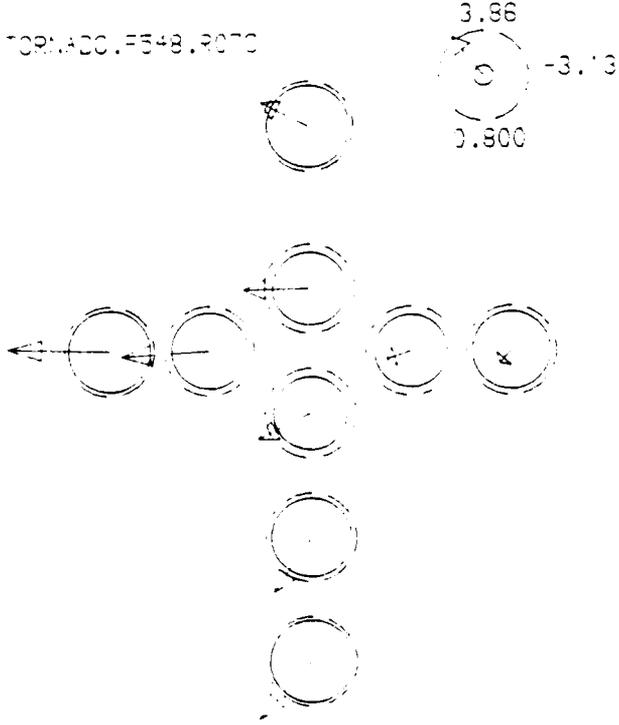
Fig 10 Example of flow survey results with aircraft sideslipping

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Flight	548	553	550	549
Pylon	front	front	middle	rear
Cruciform	fore	aft	mid	aft
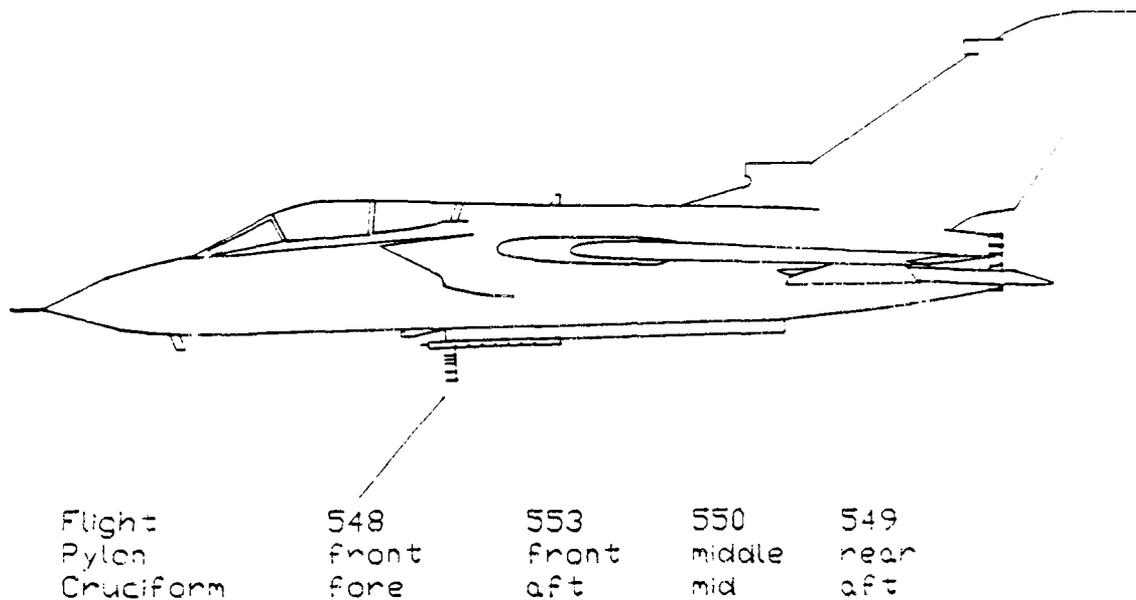
**Fig 11 Position of rig and cruciform**
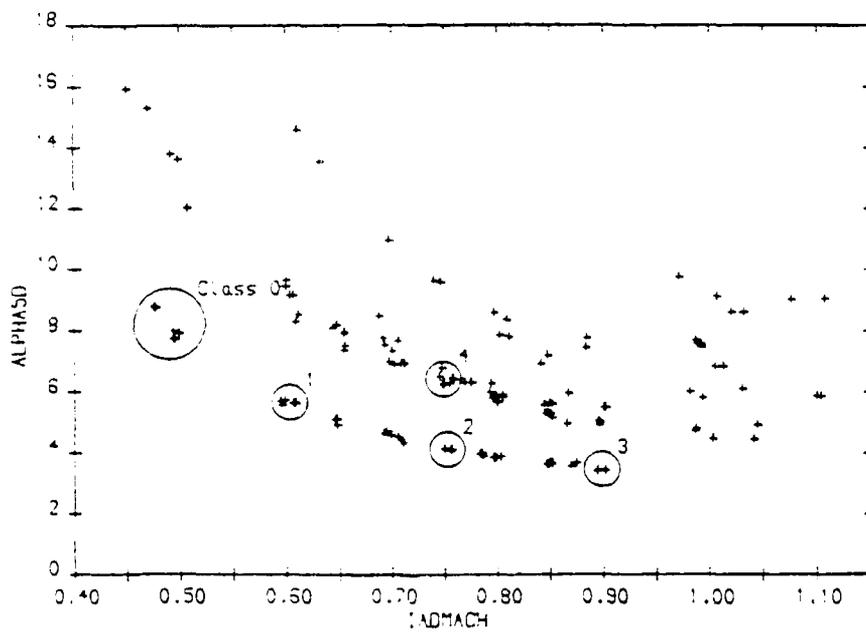
Fig 12 Flight conditions for scans at low sideslip in flights 548, 550, 553

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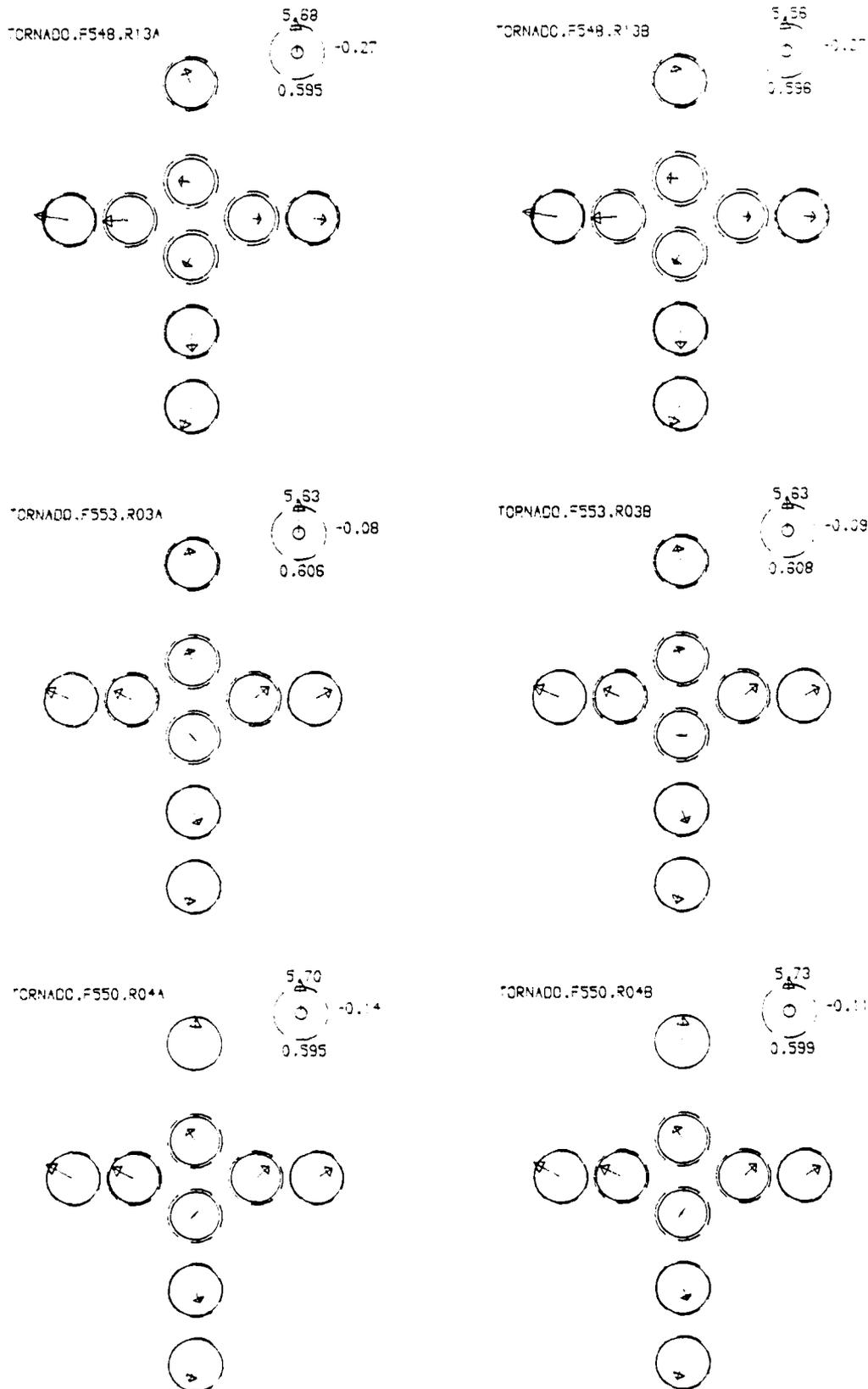
Fig 13

Fig 13 Flow surveys at Mach 0.6, mean incidence 5.65 degrees, low sideslip

REPORT DOCUMENTATION PAGE

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7b. (For Conference Papers) Title, Place and Date of Conference

"Store carriage, Integration and Release", Bath, UK, April 1990

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17. Abstract

Flight trials with a Tornado aircraft to produce full-scale experimental data for stores carriage loads, release trajectories and flow surveys are described. The instrumentation carried by the aircraft is introduced and the facilities for analysing the resulting data outlined. Some examples from flow surveys are presented. Keywords:

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