

# Electronics in Concorde

## U.K. Contribution to the Navigation, Communication, Flight Control and Other Electronic Systems

**A**IRCRAFT less modern than the *Concorde* can be considered to be divided into a large number of clearly defined sub-systems, in which computations of drift, track, attitude, airspeed and the like are carried out many times over to differing degrees of accuracy. The penalty for this approach is felt in terms of weight and cost, although, from the servicing point of view, there is the advantage that each equipment is virtually self-contained. In *Concorde* all major computations are carried out centrally, the results being electrically signalled to the various systems, and no really clear demarcation line exists between the different equipments.

*Concorde* is described as a low-wing monoplane with a slender delta wing planform. The airframe is largely constructed from a high temperature aluminium alloy although localized use is made of steel and titanium alloys at isolated "hot spots". Incidentally the nose cone reaches a temperature of 153°C and the main bulk of the fuselage 117°C

during supersonic flight. Highly stressed mechanical components in the structure have been milled from solid blocks of alloy using numerically controlled machine tools. *Concorde* has a wing-span of 83ft 10in., a length of 184ft 6in. and the height to the top of the fin is 38ft. The maximum cruising speed depends on ambient temperature and has a limit of mach 2.2 at around 55,000ft. All-up weight is 326,000lb.

### DESIGN APPROACH

Aircraft system designers of today are, in the main, presented with four possible approaches—simplex, duplex, duplicate monitored and triplex. Each method has its advantages and disadvantages in terms of safety (including reliability), weight and cost. The simplex approach consists of having only one set of equipment. Any failure results in either the equipment ceasing to function or in an erroneous output. It is up to the crew to

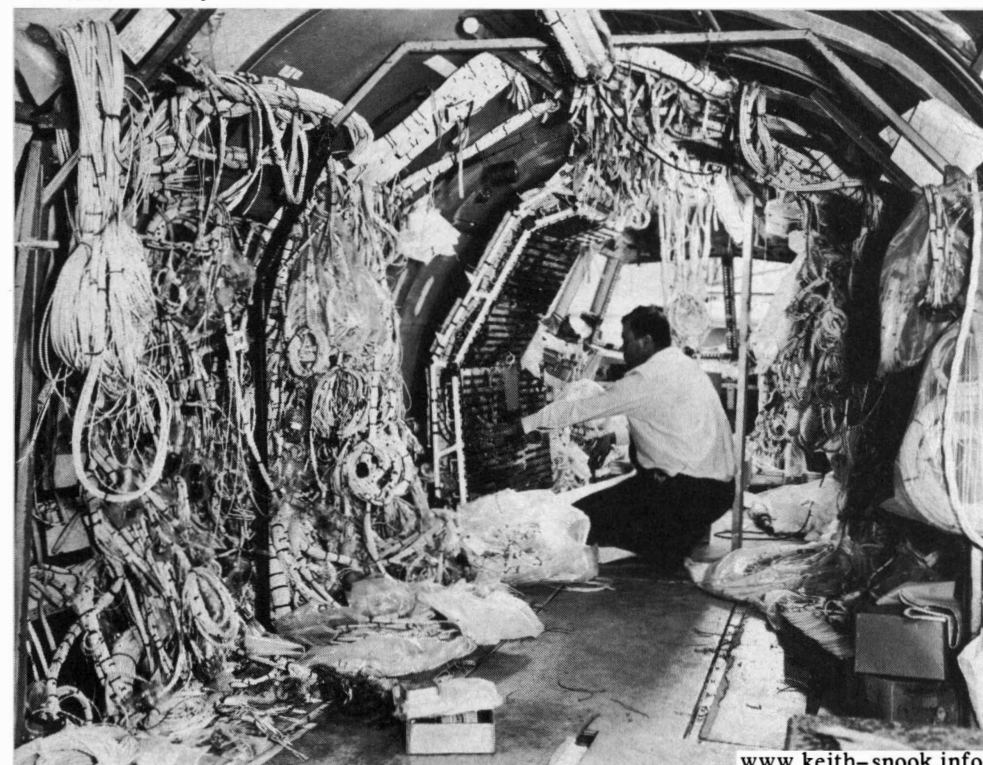
correct the effect on the aircraft of the faulty information and to take over manually from the failed equipment. Two complete sets of equipment, operating in unison, are used in a duplex system. A failure in either set will result in conflicting outputs, causing, by means of a comparator, both equipments to switch off before the incorrect output has any effect on the aircraft. It is once again left to the crew to take over the function of the failed equipment. In the duplicate monitored system two sets of equipment are again employed but a series of monitors and comparators is fitted to each set. Although both equipments are operating continuously, at any given time only one has any authority over the aircraft. Should a fault occur in a particular channel this is detected by the monitor/comparator complex and results in the serviceable equipment being given authority. In the event of the second channel failing as well it is automatically switched cut before any effect is felt on the aircraft. Such a system is said to be "fail-operative" and "fail-soft". The triplex system employs three sets of equipments operating on a majority vote basis: a different answer from one equipment results in its being switched out. From then on the system operates as described for the duplex method. It must be stated that the above is a gross oversimplification, considerable differences arising in equipments from the various manufacturers.

The main contractors in the *Concorde* project, British Aircraft Corporation and the French company Sud-Aviation, decided to employ the duplicate monitored principle for the majority of *Concorde's* control systems. Using this technique results in the aircraft carrying about two-and-a-half times more equipment than a simplex equipped aircraft.

### NAVIGATION

The degree of automation of the navigational equipment is such that *Concorde* does not carry a navigator, this function being performed by the pilots. Because of the long periods of acceleration and deceleration and other factors peculiar to this type of aircraft, conventional vertical gyroscopes are unsuitable as a basis for flight control and driving of instrument displays. Inertial platforms coupled to digital computers are therefore used as the central navigational element. An inertial platform can best be

Not really an electrician's nightmare but the flight deck wiring of *Concorde* prototype 002 being built at B.A.C.'s Filton Division. A large proportion of the cables have been supplied by British Insulated Callenders Cables Ltd.



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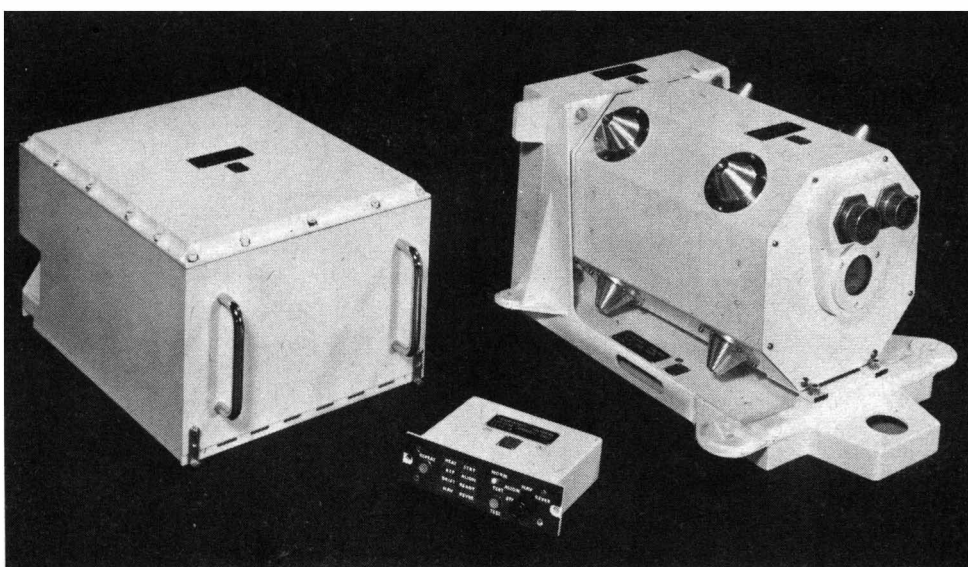
described as a platform with three degrees of spatial freedom gyroscopically stabilized relative to space but tied to the earth (as will be explained). Such a platform is said to be operating in a Schuler tuned mode. Schuler stated that a pendulum with a length equal to one earth's radius suspended with its mass at the exact centre of the earth could not be set into motion by accelerating one end. An inertial platform is stabilized relative to space using three extremely accurate, low drift, flotation gyroscopes. Digital computers calculate the corrections that have to be applied to the platform to modify the space stabilization in such a way as to keep the Z axis (vertical) pointing directly at the earth's centre and the X and Y axes pointing east/west and north/south respectively. The correction terms applied to the platform are complex and must take into account the aircraft's position over the earth's surface, the relative movements of the earth and the aircraft, the earth's curvature, centripetal force etc. The platform operating in this mode can be considered to be similar to Schuler's imaginary pendulum and is therefore unaffected by acceleration and deceleration forces.

Because the platform is stabilized in this way any movement of the aircraft is relative to the platform; this is detected by sensors and the resulting electrical signals are a measure of the aircraft's attitude relative to the earth's surface.

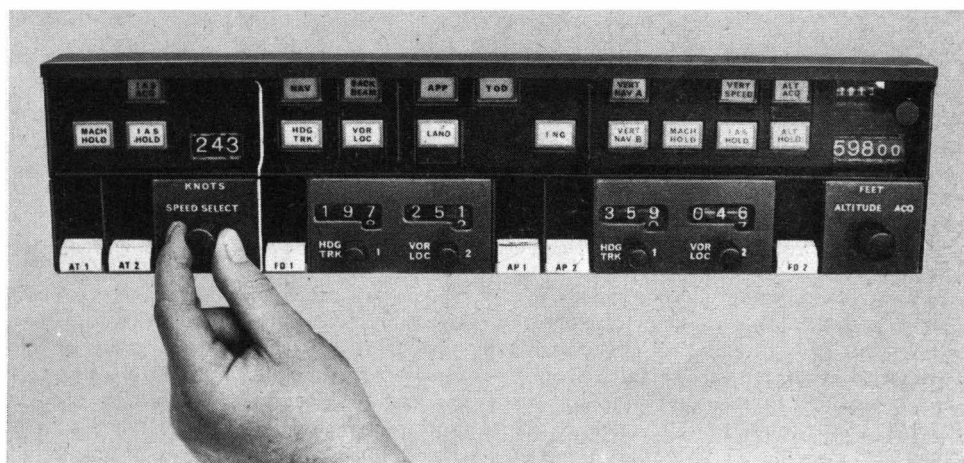
Newton's laws of motion are exploited in an inertial platform by fitting three accelerometers with electrical sensors to it. These accelerometers are orthogonally mounted (one in each axis) and their outputs can be integrated to give velocity and integrated again to provide distance flown in a given direction. From the foregoing it can be seen that an inertial platform provides a great deal of the information that is vital to navigation.

The prototype *Concordes* will carry two inertial platforms, although it is thought that three may be fitted to the first production aircraft. The navigation system to be described here is as used in the prototypes and has been developed by a consortium formed by Ferranti (U.K.) and SAGEM of France. The navigation system provides the pilot with the following information: the position of the aircraft in terms of latitude and longitude; the position of the aircraft relative to the desired route (this route is decided upon before take-off and can be modified at any time by the crew); and the estimated time of arrival at a number of reference points along this route.

The major components in the navigation system are the two previously discussed inertial platforms with associated digital computing facilities, an automatic chart display and control panel. The automatic chart display has been entirely developed by Ferranti and provides an interface allowing two-way man/machine communication. It contains a 35 mm colour film 30 feet long that can store charts covering an area 8,000 × 2,000 nautical miles at a scale of 1:2,000,000, plus two areas of 1,000 × 2,000 nautical miles at a scale of 1:500,000 for airport terminal areas. The charts are back projected on to a screen eight inches in diameter. If required, up to 100 data sheets (approach charts, tables of frequencies,



Inertial platform, control panel and associated equipment supplied by Ferranti for the prototype.



The automatic flight system control panel fitted to pre-production aircraft. The prototype aircraft are being equipped with a more conventional selector switch type of control panel.

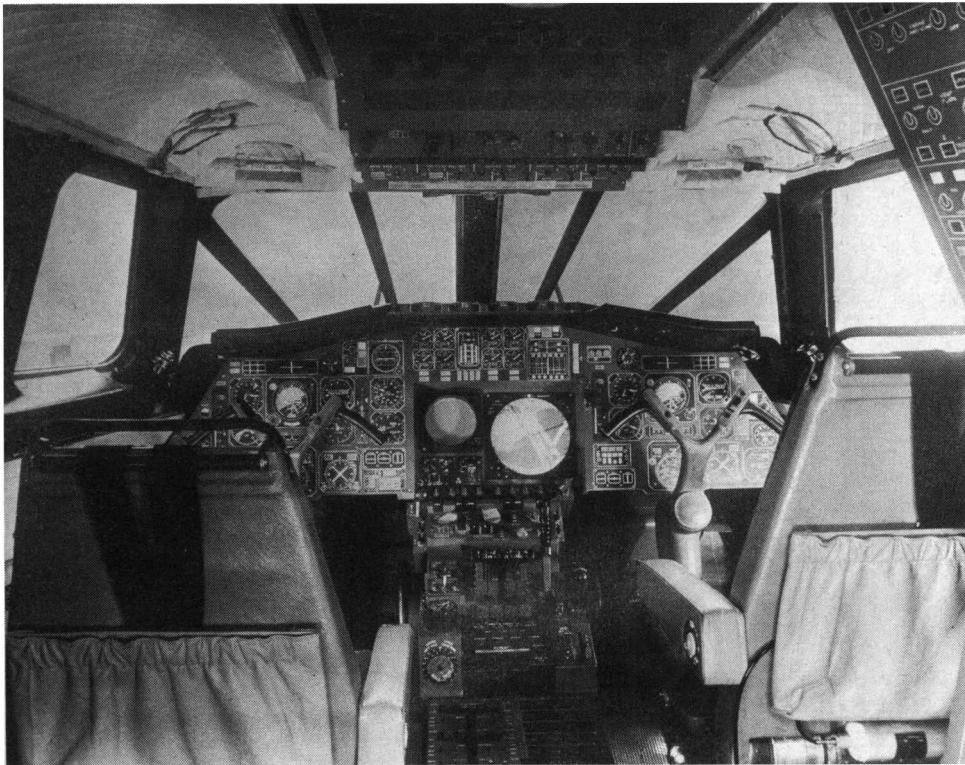
procedures, check lists, etc.) can be displayed on this screen. The present aircraft position is superimposed on the projected chart and can be in the centre of the screen or near the bottom to give a greater view ahead. The pilot can select either track or north orientation; with track orientation selected the aircraft's track always points to the top of the screen and as the aircraft turns the chart rotates. When north orientation is selected north always appears uppermost; in this case, as the aircraft turns the display's track pointer rotates.

Typically, in terminal areas, the chart will be north orientated, with the present position indicated centrally; in en route areas track orientation would be used with the present position marker offset. In the event of it being necessary to change the flight plan while airborne, because of weather conditions or some other factor, the chart is driven to bring the new destination to the centre of the screen using a joy-stick control, a button is pressed and the co-ordinates of the new destination will have been entered in the computer. The position outputs of both inertial navigators can be displayed simultaneously and in the event of a discrepancy the erring system can be corrected. V.O.R./D.M.E. (V.h.f. Omni-directional

Range/Distance Measuring Equipment) outputs also may be superimposed on the display face, among other things enabling the internal navigation equipments to be checked against them. The navigation computers also provide outputs for the automatic pilot to enable the aircraft to automatically fly along the predetermined flight path or along the flight path as modified by the pilot's manipulation of the automatic chart display. The inertial platforms, via servo-repeater systems, provide outputs of heading, attitude, velocity and vertical acceleration for use by other equipments in the aircraft. The charts for the display are being produced by International Aeradio Ltd. and some are sixteen feet long and twenty inches wide. A big problem is going to be keeping them up to date with changing air traffic control requirements.

## RADIO AND RADAR AIDS

In the Marconi doppler radar system used in *Concorde* four beams are employed with a time sharing technique. The doppler shift of each beam is measured by comparing it with a sample of the transmitted signal and the aerial is servo driven in both vertical and



The prototype flight deck mockup. The Ferranti automatic chart display can be seen in the lower left of the centre instrument panel next to the weather radar. Just below these, on the control console, is the automatic flight control panel, and just above the windscreen is the combined automatic stabilizer/artificial feed control panel. The large instrument containing a white semicircle in the centre of the side panels is the flight director.

horizontal planes until all four beams are experiencing the same amount of doppler shift. In this way the aerial is aligned with the velocity vector of the aircraft. Ground speed is obtained by measuring the amount of doppler shift, and the drift angle is obtained by comparing the fore and aft axis of the aerial with that of the aircraft. A major difficulty with a pure c.w. doppler system is caused by cross-coupling between the transmitting and receiving sections of the aerial array. Mechanical vibration also causes spurious modulation of the transmitted signal, making discrimination between this unwanted modulation and the doppler signal a difficult task. Frequency modulation is used in the *Concorde*, enabling the receiver to be made insensitive to cross-coupling and near echoes from the radome and airframe. Because the signal path from the transmitter aerial to the receiver aerial is very short the phase of the modulation on the cross-coupled signal will be practically identical to that of the transmitted signal. By mixing a sample of the transmitter signal with the received signal the receiver output can be made zero. Returns from the ground will reach the receiver after some delay, with a consequent phase difference relative to the transmitted signal. The product of mixing these signals will result in a spectrum centred on zero and sidebands on either side with a spacing equal to the modulation frequency, all sidebands being subjected to doppler shift.

The sideband power falls to zero whenever the delay between transmitting and receiving the signal is equal to one cycle of the modulation frequency, these delays corresponding to critical altitudes. If a fan-shaped aerial beam is used, returns from the ground will be subjected to a wide range of different delays and the signal strength will

seldom fall below a working level. However, signals received at near critical altitudes will have their spectra distorted, giving a false centre frequency and inaccurate speed information. To overcome this effect the modulation frequency is swept at 8 Hz between 340 and 460 kHz, causing the positions of the critical altitudes to vary and the error to average out.

In use the control unit indicates the mileage flown along the required track and an associated counter indicates the miles flown across this track, away from the required course. This information is obtained from a computer that receives aircraft heading from the navigation system, adds it to the "doppler" drift to obtain aircraft track and compares this with the required track to arrive at a track error signal. This signal together with "doppler" ground speed is fed into a mechanical ball resolver which provides outputs in terms of distance flown along and across the desired track. A signal proportional to the position of the across-track counter is available for feeding to the automatic flight control system or the navigation system if required.

The d.m.e. interrogator continuously measures the slant range distance between the aircraft and a selected ground beacon within a range of 197 nautical miles. This information is combined with aircraft heading to accurately fix the aircraft's position. The interrogator operates in conjunction with VORTAC (V.h.f. Omni-directional Range TACTical) and TACAN (TACTical Air Navigation) ground stations. Once the desired frequency has been set up on the v.h.f./navigation controller, pairs of interrogating pulses are automatically transmitted to the assigned radio beacon. The ground station, on receiving the pulse pair, replies

with a return pulse pair which is in turn received by the aircraft. By measuring the time elapsing between transmitting and receiving a reply, the aircraft equipment can compute the distance of the beacon. Should the signal be lost the equipment will continue to function in a memory mode for ten seconds, after which the interrogator initiates a "search" procedure. The transmitter provides a pulse of 1.24 kW and operates in 1 MHz steps between 1025 and 1150 MHz, and the receiver has 252 channels between 962 to 1213 MHz; the 6 dB bandwidth is 340 kHz. This equipment is being manufactured under licence from the Radio Corporation of America by Marconi's.

The weather radar for *Concorde*, manufactured by Ekco Electronics Ltd., will be used to detect stormy weather conditions in the aircraft's flight path. When such conditions are detected a new course is decided upon, the details of which are read into the navigation system via the automatic chart display. If the aircraft is being flown by automatic pilot, the navigation system will supply the automatic pilot with this information and the storm will be safely bypassed. This radar operates in the X-band at 9345 MHz; the transmitted pulse length is 6  $\mu$ s (65 kW peak) and the repetition frequency is 200 Hz; the range is 360 nautical miles (pre-production aircraft only). Each channel of the dual system carries its own transmitter-receiver, indicator and aerial stabilization system although there is a common waveguide run from the waveguide switch to the aerial.

The weather radar is one of the large number of instruments in the cockpit that can command only a small portion of the pilots' attention. When negotiating a storm this presents no problem as it becomes a prime instrument and is continuously monitored. In flight phases where the crew work load is high and weather problems are not expected, the weather radar would tend to become neglected. To overcome this problem the weather radar is arranged to continuously scan a 20 degree sector 200 miles in front of the aircraft irrespective of the setting of the indicator range scale. In the event of a target being spotted the pilot's attention is drawn to the weather radar by an "alert" indicator.

## AUTOMATIC FLYING CONTROLS

After take-off *Concorde* will climb subsonically to some 40,000ft under the control of a flight director that computes the optimum climb-out path for existing conditions and air traffic control requirements. Preparation would then be made to accelerate to supersonic speed, continuing the climb until cruising altitude is reached. At supersonic speeds the aerodynamic centre of pressure moves back along the airframe, causing the aircraft to adopt a nose down attitude. To help compensate for this a computed amount of fuel is transferred from the main tanks to a rear trim tank. However, the amount of nose down tendency is a function of mach number, which is not a constant, so, clearly, a further correction is required. This could be left to the automatic pilot but

this is inadvisable for two reasons; first, the autopilot would be called upon to make a "useless" constant correction, and secondly, in the event of the automatic pilot failing the amount of correction applied would suddenly be removed, resulting in a violent change in pitch attitude. To overcome this difficulty a system has been developed known as electric trim that has three functions: it allows the pilots to electrically signal pitch trim changes; it alters trim as a function of mach number; and it relieves any pressure on the automatic pilot by sensing any constant trim being applied in pitch and correcting for it.

Aircraft tend to oscillate in all three axes by an amount determined by the aerodynamic design, air speed, altitude, etc., and it would be very tiring for the pilot, or unnecessary work for the automatic pilot, if these oscillations were allowed to go undamped. The automatic flight stabilization system employed to make these corrections uses a total of six rate gyroscopes actuating the flying controls via servo systems. A rate gyroscope is either electrically or mechanically spring restrained and has an output proportional to the rate, as opposed to the amount, of displacement. It will be realized that such a system will try to oppose any deliberate manoeuvres. However, the system has only limited authority and acts as an efficient damping mechanism.

The lateral and longitudinal control channels of the automatic pilots are completely separated and each automatic pilot is supplied with information from independent sources. A single control panel is employed for the automatic pilots, the automatic throttle systems and the flight director system. The required function is selected and a choice is made between automatic pilot and flight director. If the last-mentioned is chosen the pilot controls the aircraft in response to visual guidance information presented by the flight director. In the former case the function is carried out automatically. This would seem to imply that the functions available using the automatic pilot or the flight director system are identical. This is the case, with one exception which occurs when the automatic pilot is switched to "manual". Under these conditions the aircraft will maintain the attitude existing at the time of engagement, the attitude references being supplied by the inertial platforms. Other functions provided by the flight system in the longitudinal axis are: altitude hold, mach and airspeed hold, vertical speed hold and altitude capture. For the first three functions, if selected, the aircraft will hold each condition as it existed at the time of engagement. Altitude, mach and airspeed references are obtained from an air data computer. The altitude capture facility allows the pilot to preselect any required altitude; when the aircraft reaches this height the flight system reverts to the altitude hold mode. Automatic vertical navigation is also possible, and in this case the automatic pilot/flight director follows information provided by a vertical navigation computer.

In the lateral axis the manual and heading functions of the flight system are self-explanatory in the light of what has already been said. Lateral navigation may be selected and in this case the flight system responds to

information received from the navigational computer. The signals used are track error and rate of change of error with respect to the programme stored in the navigational computer.

A VOR/LOC mode is available that captures and holds a VOR or localizer beam, the capture angle being selected by the pilot.

The automatic pilot is capable of carrying out landings in Category 3a conditions (visibility insufficient to land manually but good enough to steer the aircraft on the runway). The autopilot will hold the aircraft on the localizer and glide path beams and will initiate the flare and land sequence as indicated by the radio altimeter. Should it be decided to abort the landing, pushing the throttle forward will put the flight system into the "go around" mode. This disengages the automatic throttle system and causes the take-off director computer and the flight director computer to provide guidance information that ensures that a safe overshoot path is followed.

The automatic throttle system controls engine r.p.m. so that the mach number or airspeed existing on engagement is maintained, or alternatively, the desired airspeed can be pre-selected. The system obtains reference airspeed and mach number from the air data computers and a longitudinal term from the inertial platforms.

The control panel for the automatic flight control system represents a departure from standard aeronautical techniques in that push-button selector switches have been employed for mode selection; this practice has been frowned upon in the past on the grounds of reliability. Integrated circuit protection logic has been designed to work in conjunction with the push-buttons that will lock out a faulty mode even if the associated selector button is jammed in the "on" position.

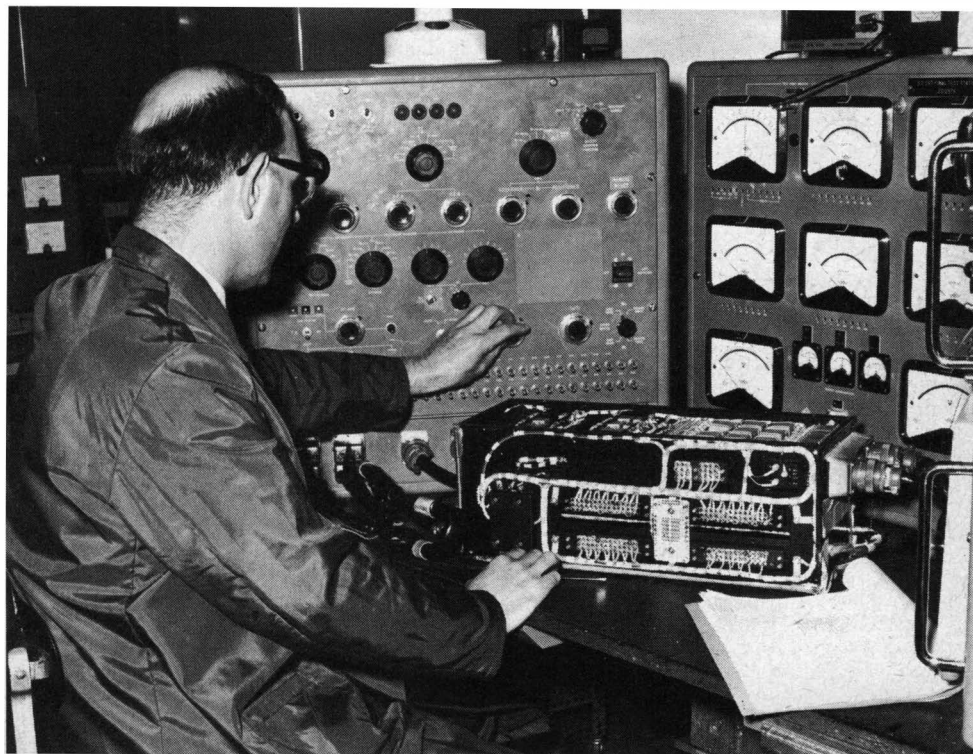
The automatic flight system described has been designed by a consortium including Société Française D'Équipement pour la Navigation Aérienne (S.F.E.N.A.) and the Navigation and Control Division of the Bendix Corporation of America headed by Elliott Brothers as prime contractors.

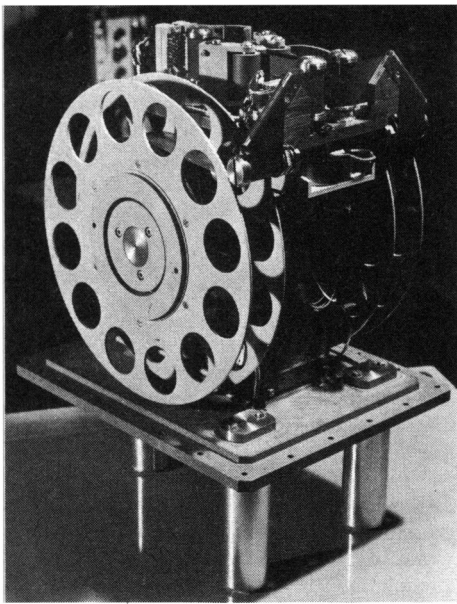
## COMMUNICATIONS

Airborne selective calling units, known as Selcal, are used to relieve the crew of the continuous and tiresome task of aurally monitoring the radio communications channels. To this end each aircraft is given a four-letter code, each letter corresponding to one of twelve audio tones. This code is set in on the front of the Selcal unit using two pairs of knobs which select tuned reeds. The ground station transmits a two-pulse code signal, each pulse containing two audio frequency tones in the band 312.6 to 977.2 Hz. The aircraft receives these tones and applies them to the Selcal unit, where, after amplification they are applied to the tuned reeds. In the called aircraft all four reeds will vibrate and the appropriate warning will be given to the crew.

Collins Radio Company are supplying the h.f. transceivers. These are s.s.b. equipments for long range voice, c.w., data or compatible a.m. communications in the 2.0 to 29.999 MHz frequency range. Tuning is automatic in 1 kHz steps by means of an operator's remote control box, the operating frequency being displayed digitally. Nominal transmitter power is 400 watts p.e.p. in s.s.b. or 125 watts in compatible a.m. All injections to both the transmitter and receiver are phase locked to an internal frequency standard with a stability of 0.8 parts per million per month. Channel selection time is eight seconds. The receiver sensitivity on s.s.b. is 1

One of the prototype versions of the engine control computer undergoing final test at Ultra Electronics, Western Avenue factory, prior to delivery to Bristol Siddeley Engines.





High density precision tape recording head used in the *Concorde* prototype accident recording system being produced by Elliott Automation. The system records 300 parameters and is protected for crash loads and is automatically ejected if submerged.

$\mu\text{V}$  for a 10 dB (signal + noise)/noise ratio and for a.m. it is 3  $\mu\text{V}$  modulated 30 per cent at 1 kHz for a 6 dB (signal + noise)/noise ratio.

## OTHER ELECTRONIC SYSTEMS

The engine control system has been designed as an electrical link between the crew and the engines. Normal control actions such as throttle opening and fuel flow are under direct crew control, but many other parameters are altered automatically by computers designed by Ultra Electronics Ltd. These include controlling fuel flow during start-up and in-flight re-lighting, control of high pressure spool speed, adjustment of idling fuel flow to prevent flame out, maintaining acceleration and deceleration throttle inputs to safe levels, limiting jet pipe temperature, correcting nozzle area, air intake control and controlling many other parameters. The variable geometry air intakes controlled by the system decelerate the supersonic free air stream to a fairly low subsonic value before allowing it to enter the engine.

The *Concorde* prototype 001 will have two E.M.I. television cameras fitted, one of which will be mounted on the nose wheel to give an improved forward view whilst taxiing. This camera has a 90° wide angle lens. The second will face the rear, enabling the landing gear and the underside of the aircraft to be viewed. In addition, for the prototype 002, E.M.I. are supplying three half-inch cameras for mounting in the engine nacelles and two one-inch cameras for viewing the wings and tailplane. During periods of high sunspot activity, solar radiation could become a problem at the altitudes at which *Concorde* will be flying. A radiation detector is being built by A.W.R.E. to enable the amount of radiation to be measured. Should this ever exceed a safe level, *Concorde* will be forced to fly subsonically at a

lower altitude. It is understood that the fuel penalty resulting from this is not high.

Aircraft instruments of the past that required inputs of height, rate of climb, air speed and mach number had to rely on a jungle of pipes relaying pitot and static air pressures to them to derive the necessary information. These pipes were very vulnerable and a good deal of servicing effort had to be spent in tracing microscopic leaks, often in inaccessible parts of the aircraft. In *Concorde* a simple pipe system carries the air pressures to two central air data computers that are being manufactured in France by Crouzet. These computers then provide electrical outputs for other equipments proportional to: altitude, airspeed, mach number, vertical speed, total temperature, static temperature, true airspeed, angle of attack and side slip angle.

An Elliott flight recording system is incorporated which collects speech, analogue and digital information from more than 300 points during a flight of up to twelve hours. This information is "conditioned" in integrated circuit computers before being recorded on magnetic tape. The crash-proof capsule containing the recording mechanism is ejected if submerged, whereupon it floats to the surface and a radio beacon emits a homing signal.

A good deal of the engine instrumentation is also being manufactured by Elliott's. These take the form of miniature indicators with, in many cases, a certain amount of the computing circuitry built into them. These instruments are mounted on the flight engineer's control panel with "essential service" indications duplicated on the pilot's panel.

The fuel flow system comprises a transmitter and complementary indication for measuring the quantity of fuel consumed, rate of fuel flow, and the amount of fuel remaining. The flow sensor measures the mass flow rate of fuel passing in the line, determining the heat content and thus the propulsive content. The transmitter has an accuracy better than 1% over a 9:1 flow rate range at  $20^\circ\text{C} \pm 5^\circ\text{C}$  whilst the flow rate indicator has an accuracy of  $\pm 0.5\%$ .

The electrical installation serves all other

systems and has to supply a load of up to 61 kVA. As has already been stated, all aircraft essential systems are at least duplicated, and to preserve this safety margin each equipment of a duplicated system is fed from an independent power source. The four 8,000 r.p.m. brushless alternators each have a nominal continuous rating of 40 kVA at 400 Hz 200/115 V. They automatically self excite and synchronize to deliver their outputs in parallel pairs. The d.c. busbars are supplied via transformer-rectifier units and charge two standby nickel-cadmium batteries. A 1.8 kHz supply for the flying control signalling circuits is derived from two 26-V single phase static inverters supplied from the essential services battery busbar. Loss of one generation channel leaves all services fully operational by employing transfer techniques. Loss of two channels leaves general services unimpaired but the electrical de-icing equipment becomes inoperable. In the unlikely event of a complete four engine flame out the battery capacity permits a gas turbine driving a generator to be started which will maintain essential services.

To speed up communications between Britain and France on matters dealing with *Concorde* a private wire circuit between London and Paris has been installed. The new link has been set up in co-operation with both the British and French Post Office authorities. It will carry a wide variety of communications traffic including teleprinter messages, telephone conversations, high-speed transmission of punched and magnetic tape data, and facsimile transmission of drawings or messages. The circuit was primarily installed to facilitate radio contact with *Concorde* flight test crews when prototype testing begins in the spring. It will enable ground engineers in Toulouse to operate a remote control radio-relay station at Filton, providing a three-way link between Filton, Toulouse and the aircraft. This is necessary since the range of the v.h.f. radio equipment in *Concorde* is limited to about 600 miles and contact with the aircraft may be lost on the proposed test flights over Northern Europe. [www.keith-snook.info](http://www.keith-snook.info)

An example of the engine instruments used on *Concorde*. The photograph shows a section of the flight engineer's panel. Some of the more important instruments are duplicated on the pilot's instrument panel.

