The Place of Inertial Navigation in the Navigation of Transport Aircraft

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SUMMARY

This paper examines how inertial navigation has come to be a requirement for civil airline operations and how it fits into the spectrum of available navigation systems. Some recent advances in technology are highlighted which have enabled an economically attractive solution to be devised and considerations of reliability and maintainability are explored.

Some ten years ago I was invited to give a paper to the Royal Aeronautical Society on the subject of inertial navigation. In the course of this paper I indicated the probability that inertial navigation which, at that time, was a high-grade scientific toy, suitable only for the navigation of very expensive missiles, would one day form part of the standard navigational equipment of commercial aircraft. We now appear to be very close indeed to that day and it is, therefore, perhaps pertinent to enquire, first, why has inertial navigation become a need for modern civil aircraft and, second, what are the advances in technology which have enabled it to take its place alongside more conventional means of navigation?

Before examining how inertial navigation has become a necessity I should perhaps, for those who are not in day-to-day contact with aircraft navigational problems, explain that inertial navigation is a system of dead-reckoning navigation in which a set of reference axes are determined by a gyroscopically stabilised platform. The accelerations of the platform along these axes are measured by high precision accelerometers mounted on it and are then integrated twice in order to obtain the distances travelled in those axes. This is illustrated in Fig. 1. It is customary and convenient to establish two of the axes at right-angles to each other and in the horizontal plane normal to the local vertical while the remaining axis is vertical. It is sometimes arranged that one of the horizontal axes lies in a North/South direction. However, this
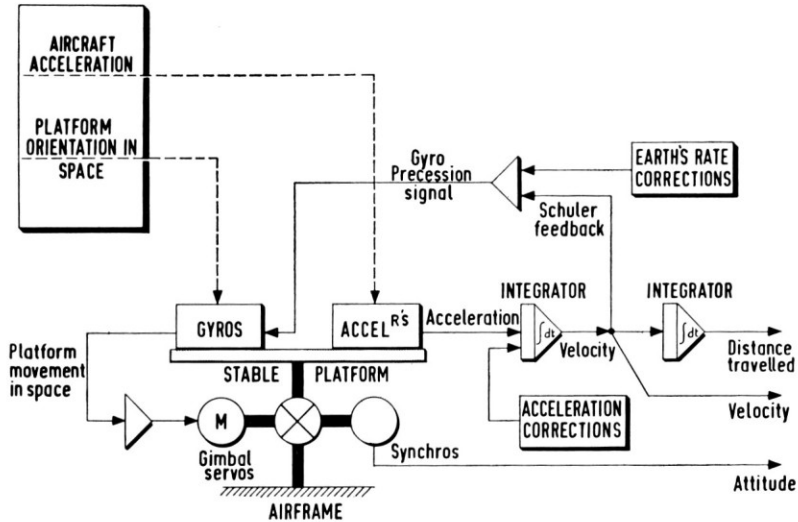
Fig. 1 — The basic inertial navigator

has disadvantages when flight over or close to the Poles is concerned, since rapid rotation about the vertical axis would then be required. For this reason it is usually more convenient to make the platform define grid heading rather than true heading, at the expense of some additional computation. Such a system can over-fly the Pole without loss of accuracy.

To maintain the platform levelled to the local vertical, the two horizontal axes are made to precess at a rate corresponding to the sum of the earth's rate and the angular velocity of the aircraft about the earth. The latter term is, of course, derived from the integral of acceleration: the resulting arrangement generates an oscillatory loop, known as the Schuler loop, which has a natural period of about 84 minutes.

This loop, although undamped, acts to keep limited the errors in the system. For example, acceleration measurement errors, which one might expect to generate rapidly deteriorating positional accuracy, cause limited position errors. Vertical gyro drift causes a corresponding velocity error and to a large extent defines system accuracy. To achieve accuracies of the required order, the day-to-day wander of the vertical gyros must be held down to something less than about 0·03 degrees per hour and preferably, should be better than 0·01 degrees per hour. The performance of the azimuth gyro is critical for the long flight times of civil aircraft and should be kept to the same limits.

In most inertial systems the axes are initially aligned in an automatic manner while the aircraft is stationary on the ground. The vertical is obtained by precessing the gyros so as to null the accelerometer outputs: azimuth

alignment is usually made by automatic gyro-compassing. This operation depends on the fact that the rate of rotation of the earth about an axis which is pointing accurately East and West, is zero. The alignment procedure is of some considerable practical importance as it determines the time required to make the inertial navigator ready. Immediately after switch-on the gyros require something of the order of one minute to run up to normal operating speed and a significant period of time is then required in order that the gyroscopes, accelerometers and the entire platform equipment may reach a suitable temperature. Most inertial quality gyroscopes and precision accelerometers are capable of operating accurately only when their temperature is close to some predetermined value and also, when the temperature differential across the gyro is reduced to some quite small value. These values do, of course, vary considerably from one type of instrument to another, but periods of 2–15 minutes are customarily required for temperature stabilisation, the time involved being largely a function of the temperature differentials which can be permitted inside the gyroscope and these depend upon the details of construction.

Erection to the vertical is a comparatively high-speed operation taking only a minute or so, but unfortunately gyro compassing in azimuth is a somewhat more difficult operation. The platform may start the gyro-compassing period with an arbitrary unknown heading, with zero initial horizontal precession rates. After a period of time the effect of the earth's rotational rate will cause the platform to tilt. This tilt is detected by the accelerometers mounted on the platform and is fed back so as to generate in each axis the correct precession required to keep the platform level. Knowledge of these precession rates enables the platform heading to be computed. It will be appreciated that the measurement of very small angles of tilt arising from the earth's relatively slow rotation, in the presence of disturbances, implies a filtering problem. These disturbances are due to things such as vibration of the aircraft arising from wind gusts, passenger entry, baggage handling, refuelling, etc., all of which will be sensed to some extent by the accelerometers. The net result of all this is that the action of gyro-compassing may take some 5–10 minutes to reduce the initial errors to some acceptable value, usually of the order of three minutes of arc in these latitudes. Since the angular rate of rotation in a horizontal axis, due to earth's rotation, decreases from 15° per hour at the Equator to zero at the Pole, it will be seen that gyrocompassing can become a hazardous operation in higher latitudes and adequate performance in this respect is not possible above 80° North or South. In practice this imposes no real restraint on the use of inertial systems in civil aircraft. Alignment of the platform in the air, although technically possible, is extremely difficult: an accurate vertical is difficult to find, due to accelerations of the vehicle and gyro-compassing becomes impossible unless extremely accurately known velocities are obtainable from other sources.

The possession of an inertial navigator brings other benefits in terms of ability to effect accurate short-term control of the aircraft. Such a stabilised platform can evidently be used as an accurate source of information about attitude and will not have the errors found in less complete gyroscopic systems. When fitted with a vertical accelerometer it can be used, in combination with radio and barometric information, for vertical navigation. The provision of measurements of accelerations and of angles which are not subject to perturbations, is becoming more important to flight control systems as the performance of aircraft increases.

We see, therefore, that inertial navigation represents a complete dead-reckoning navigational aid, entirely independent of sources of information external to the aircraft but requiring instrumental accuracies of a high order. The complexity of the system is fairly great as it involves not only a stable platform carrying accelerometers, positioned in accurately known directions, but also a computer of some considerable capacity. This computer processes the information obtained from the accelerometers, gives precession signals to the gyroscopes and also computes latitude, longitude and steering signals.

It is now necessary to consider aircraft navigation to see how an inertial system fits logically into the evolutionary pattern of equipment and how it makes an advance possible beyond the limitations of present installations.

It is customary to divide the navigation process in an aircraft into two discreet phases. First, there is the intermittent process of determining one's position, known as fixing. This process may be conducted by a variety of means, specifically by radio aids, such as VOR or by direct visual observation, or by radar means, or by hyperbolic means such as Loran C. The essence of such navigation is that, although it enables a position to be determined at a given point in time, it gives little information as to the direction and magnitude of the velocity vector of the aircraft, which is the parameter required to be able to predict where the aircraft will be at some time in the future. Since such vector information is essential to the operation of any civil aircraft, other aids are required to fill in the structure of navigational information. Such aids are frequently of a dead-reckoning character. They may, for example, be a measurement of true air speed coupled with a knowledge of wind direction and used in conjunction with a magnetic compass. This method has the merit of extreme simplicity and the usual corresponding disadvantage of low accuracy. A refinement of some considerable benefit is to determine ground speed by means of a Doppler radar equipment and to use this in conjunction with a magnetic compass to obtain dead-reckoning information. This is a marked improvement on the true air speed situation since it does not involve a knowledge of wind direction or velocity and may, in fact, be used to determine them. However, the inherent limitations of the magnetic compass, which are not only instrumental limitations but also limitations of our knowledge of magnetic variation over the world's surface, lead to a relatively

inaccurate result. Attempts to improve the performance of the heading reference lead to a solution which is comparable in form and complexity to an inertial platform and thus, logically, to a full inertial installation.

Further disadvantages can arise in that, over certain types of terrain, the Doppler radar may not yield an adequate return. The reflections from the earth's surface which are needed by the Doppler radar in order to determine speed, may be inadequate in their amplitude and, hence, lead to an apparent unreliability of the equipment. This is particularly true over the sea when a smooth surface will yield no return or, alternatively, the signal will be contaminated by surface motion due to wind.

Many measurements of the accuracy of Doppler/magnetic systems have been published and from them it is possible to conclude that over certain routes and, with particular precautions, the overall performance is adequate for present separation standards. However, the potential for improvement is limited and the problems of installation and of reliability will always exist. On the other hand, most manufacturers of inertial navigation equipment are currently quoting a mean time between failures of the order of 1000 hours with accuracies of between 1–2 n.m. per hour. Such experience as exists in civil airlines indicates that these figures are indeed obtainable, although it would perhaps be premature to say that they are being achieved at the moment, and it would seem to me that the very fact that inertial navigation is virtually independent of outside sources, other than power supplies, renders it inherently a more reliable equipment then those which rely on the vagaries of radio transmission.

Inertial navigation, therefore, offers the possibility of a fine structure navigational aid more than competitive in both accuracy and reliability with the best alternative aid at present available, besides being a long term dead-reckoning system which is sufficiently accurate to avoid the necessity of obtaining radio or visual fixes *en route*.

The determination of civil operators to employ inertial systems is clearly shown by the efforts which they are now jointly making to draw up an agreed specification (ARINC No. 561). The impetus for this activity was brought about by two main stimuli: first, the realisation that a Schuler-tuned attitude reference is essential for the S.S.T. and, second, Pan American's action in equipping their fleet with an inertial navigator. Boeing have now expressed their desire to put a system as defined by the agreed specification into the 747, on the understanding that they will cover any aspects which may not be adequately specified for that application.

Agreement has now been reached on the system modes and facilities, the size and shape and the inputs and outputs. There remain outstanding some aspects of the display, a lot of detail and the question of accuracy. However, some guidance is given in this last respect by an F.A.A. document on certification, dated July, 1965, which states:

'On a 95% probability basis the indicated position should correspond to the true position within an allowable error of ±20 n.m. (cross-track) and ±25 n.m. (along-track) for flights of any intended duration.'

It is noteworthy that the point has been accepted that a stand-by battery of limited capacity is needed to bridge power failures and transients. In equipment of this nature the sensitivity to such interruptions is most marked, particularly when digital computers are employed.

The navigator will generate steering data for either transmission to the autopilot or display and will store at least five way-points, settable in flight or on the ground. It will give outputs suitable for a data link, thus allowing additional digital display of some parameters, such as time-to-go to next way-point, or their transmission to the ground. Generally speaking the system will generate all the useful navigation and steering data that an unassisted inertial navigation system can provide.

It will have a full polar capability and will operate in grid heading. It will also have an attitude reversion mode in which the platform serves as an attitude reference independently of the computer. It will be fully manoeuvrable (707s have reached 100° of pitch!). Self-monitoring and self-check is mandatory, although the extent of it is as yet undecided.

It should be added that the ARINC 561 specification postulates for S.S.T.s the use of an associated system which will do all the additional things that such an aircraft might require: vertical navigation, vertical profile guidance, data processing, etc. So far this associated system has not had any consideration beyond providing for the inputs it may require.

It is evident from what has been agreed that the philosophy is to have a small, compact, universally usable, automatic inertial navigation system doing only the basic inertial navigation function with adequate accuracy. Scope for doing all the clever things that one can do with navigation systems is to be provided by taking the basic quantities from a data link output, so that they may be used as desired in a separate box.

In fact, lest anyone should think the result is too simple, the system has a large complement of facilities and outputs, from attitude to steering information. Such systems of comparable complexity are now in the offing and the ARINC specification would appear to give an extremely healthy start to civil nertial navigation systems, by demanding a reasonable degree of sophistication combined with the capability of extension.

It can be seen that an equipment conforming to these requirements will provide a self-contained continuous navigation system giving an accuracy more than adequate for forseeable air traffic control requirements, weighing 80 lb. or less. It will make a human navigator unnecessary, will give close automatic control of flight path in plan and in height and will provide high quality signals for automatic throttles and automatic landing. Trials of
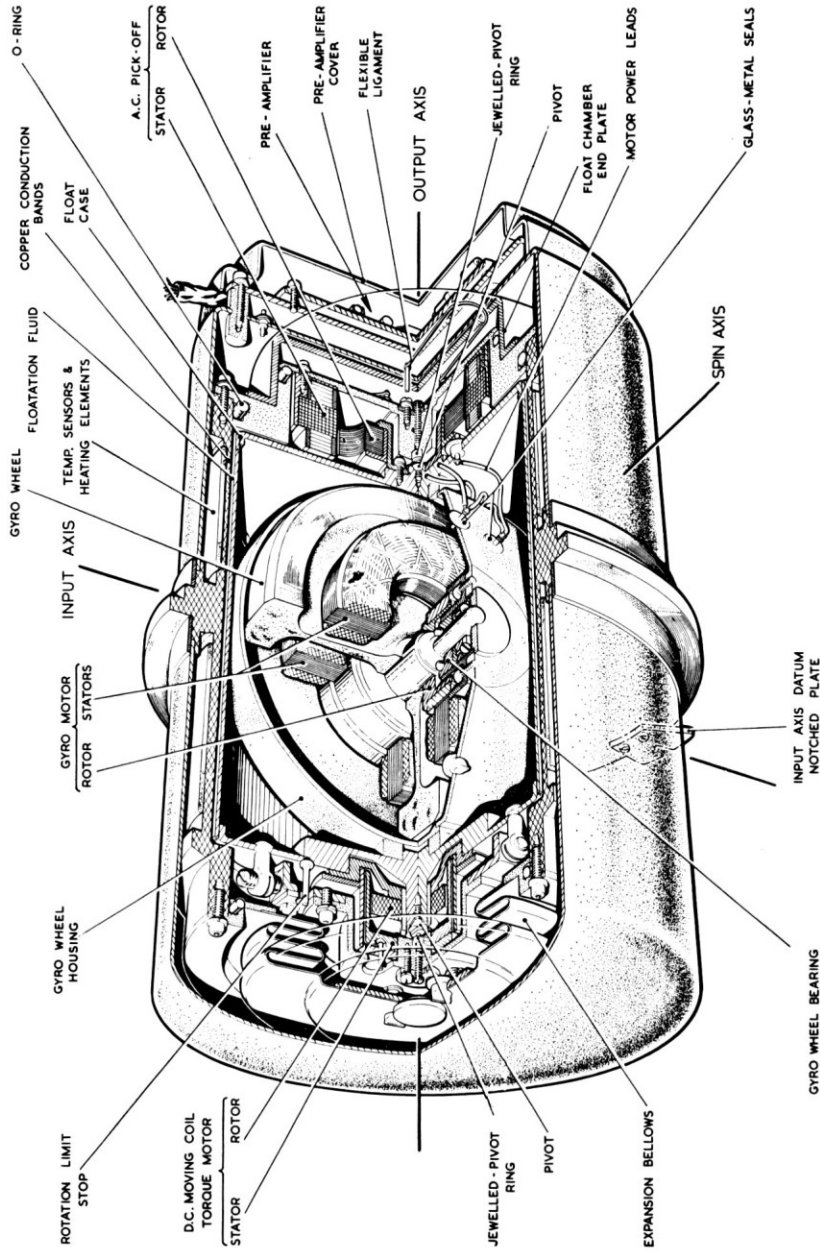
O - RING

A.C. PICK - OFF
STATOR   ROTOR

PRE - AMPLIFIER

PRE-AMPLIFIER
COVER

FLEXIBLE
LIGAMENT

JEWELLED - PIVOT
RING

PIVOT

MOTOR POWER LEADS

GLASS-METAL SEALS

OUTPUT AXIS

COPPER CONDUCTION
BANDS

FLOAT
CASE

FLOAT CHAMBER
END PLATE

GYRO WHEEL

FLOATATION FLUID

TEMP. SENSORS &
HEATING ELEMENTS

INPUT AXIS

SPIN AXIS

GYRO MOTOR
ROTOR   STATORS

GYRO WHEEL
HOUSING

INPUT AXIS DATUM
NOTCHED PLATE

ROTATION LIMIT
STOP

D.C. MOVING COIL
TORQUE MOTOR
STATOR   ROTOR

JEWELLED - PIVOT
RING

PIVOT

EXPANSION BELLOWS

GYRO WHEEL BEARING

FIG. 2 — Section of flotation rate integrating gyroscope

equipment suitable for airline use have shown that performance of the required accuracy and serviceability is currently obtainable and one must ask oneself whether it has real economic advantages and how it has been achieved in engineering terms.

The economic advantages to the operator of an inertial installation can be shown to be very real. Studies show that a dual system should cost about one-fifth of the human navigators which it replaces and that even the initial period of excess cost is not too serious. Depending upon the rate of replacement of navigators and upon the magnitude of any redundancy payments, the break-even point will be found somewhere between three and six years. The economic position is not so much in doubt as that regarding the general acceptability of inertial systems for retro-fit to existing fleets. For new aircraft the pattern is now firmly established.

Economic acceptability has come about from recent engineering advances affecting the basic precision components of the system.

The most important component in any inertial navigation system is the gyroscope and it is here that, until a short time ago, were to be found the obstacles to its adoption by civil aircraft operators. The technology of inertial guidance grew up around the single degree of freedom floated rate integrating gyro, which has a number of advantages for ship, missile and military air-craft navigation. Such a gyro is shown in Fig. 2. It is an intrinsically expensive instrument which cannot be repaired without elaborate equipment and a high degree of specialised skill, so that the cost of repair is about 70% of its initial cost. Furthermore, until recently, the bearings of the gyro wheel had a strictly limited life. This limitation arose from the high rotational speed, coupled with the necessity for a preload sufficient to prevent mass shifts under acceleration: the introduction of gas-supported bearings has eliminated this problem but the other difficulties remain. Development of the free rotor gyroscope with two degrees of freedom and having a gas bearing has offered a way of obtaining an economic solution by virtue of its relative ease of manufacture and by reduction of the number of gyros from three to two. This form of instrument is shown in Fig. 3. With the gas bearing the running life is indefinite, but the number of starts and stops is limited.

It can be shown that in airline operation this is unlikely to be important, since the life will probably be comparable with that of the airframe, but it is interesting to know that should an accumulation of debris cause the rotor to fail, it will not do so in flight but on initial switch-on. In some gyros, particu-larly of the unfloated variety, cleaning of the bearing is a relatively simple matter and when it has been done the instrument will be restored to its original condition.

Another important advance which has been made is in methods of reducing the effects of friction in gyro gimbals and of eliminating systematic gyro wander due to spurious torques.

BALL (FIXED)
BEARING GAP
ROTOR

MANGANIN SLEEVE
INDUCTION TORQUER STATOR
WINDAGE SHIELD

CAPACITOR PICK-OFF
ELECTRODE

INSULATION

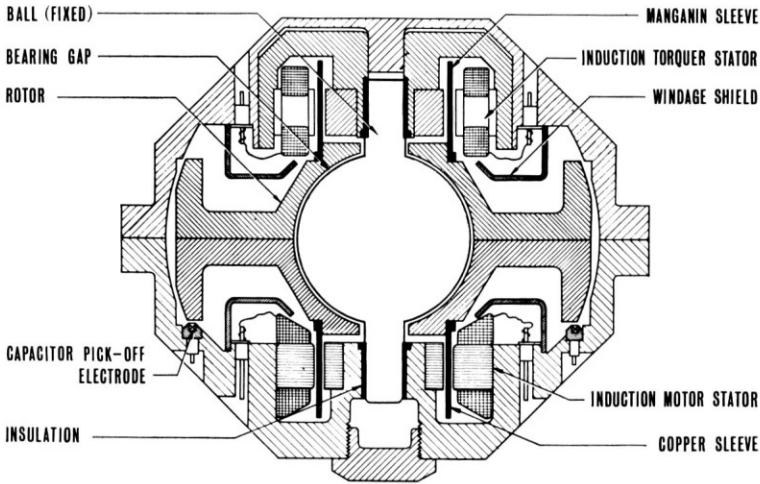INDUCTION MOTOR STATOR

COPPER SLEEVE

FIG. 3 — Section of free rotor gyroscope

Techniques of slow rotation and counter-rotation of parts of bearings have reduced gimbal friction to extremely low values and this feature will be found in some platforms and will result in significant improvements. Figure 4 illustrates the use of a rather different principle in which continuous slow rotation of a gyro case results in commutation of the major disturbing

SPIN
MOTOR
TORQUE

ROTATING SPURIOUS
TORQUES

SPIN
MOTOR
TORQUE

GYRO ROTOR

SPURIOUS
TORQUES

GYRO ROTOR

RESULTING NOD
(NO NET DRIFT)
GYRO DRIFT
WITH CASE-ROTATION

RESULTING DRIFT
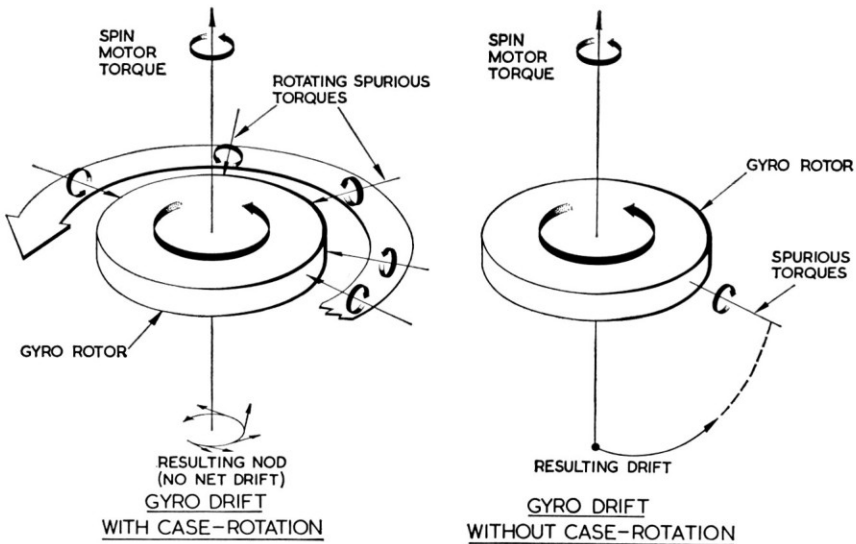GYRO DRIFT
WITHOUT CASE-ROTATION
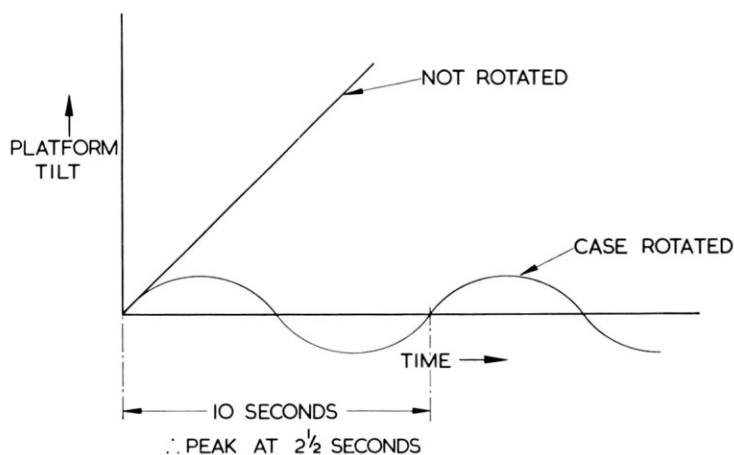
FIG. 4 — Principle of gyro case-rotation

FIG. 5 — Effect of case-rotation

torques. This has the effect, as shown in Fig. 5, of averaging and thus of eliminating the major and systematic drift. In this way performances of about 0·003 degrees per hour have been obtained from gyros whose accuracy would otherwise have been an order of magnitude worse. This elimination of systematic gyro errors has an important effect upon the pattern of error of the navigation system. In the past it has been observed that this pattern has been broadened, as would be expected if dominant systematic contributions were present. This means a high probability of the occurrence of relatively large errors: by means of averaging of gyro wander the distribution becomes much more nearly normal and the expectation of large navigational deviations falls significantly. The overall effect of such measures has been to increase system performance while, at the same time, enabling gyros of lower inherent accuracy to be employed.

Much thought has gone into the problems of self-monitoring and it is now reasonable to claim that errors equivalent to a velocity discrepancy of ten feet per second can be detected. The engineering techniques employed to do this owe much to the work done on automatic landing flight control systems and involve attention to every detail of the electrical and mechanical design.

With a platform having two free rotor gyros it is evident that a redundant axis exists. This redundant axis may be used as a sensitive test of gyro performance. Full accelerometer self-monitoring usually implies a redundant accelerometer axis. Other functions of the platform and computer are monitored by techniques which are now highly evolved.

Such a self-monitored system using the latest techniques appropriate to civil use can be shown to have a probability of failure of about one in 2500 hours and an automatically undetected failure of about one in 50,000 hours.

Considered purely as a precision attitude reference, the probability of failure is about one in 6000 hours. It is clear that a twin installation will be very reliable indeed and it is probably a somewhat meaningless exercise to calculate a figure at this stage.

The problems of the computer for inertial navigation are similar to those of most airborne computers. The introduction of micro-electronics has enabled reliability to be increased to acceptable levels and has resulted in the ability to provide increased facilities in less space and with less weight. The interface between computer and platform has been simplified by the use of a variety of electronic techniques which may best be described as neither digital nor analogue, but hybrid. Displays have followed contemporary practice and are in no way exceptional.

I think that we may now safely state that inertial navigation for civil airlines has arrived. The necessary accuracy is achievable and the appropriate economy is ensured by progressive increases in the life of the precision components, together with advances in electronic reliability. It will remain a relatively high cost piece of equipment on account of the accuracy demanded, particularly from the gyros, and any attempt to cut the initial cost too rapidly and imprudently will lead to reductions in reliability, with increases in maintenance.

Use of such systems poses no special restraints upon the operators and will ensure higher standards of safety in dense traffic. Additional benefits will be obtained in terms of vertical navigational capability and improved flight control.

Attempting to look ahead for a further ten years, I do not consider it probable that the inertial platform erected to the local vertical will be supplanted. While purely navigational considerations may indicate the desirability of other configurations, it seems to me that its other role as a Schuler-tuned attitude reference, with a simple attitude reversion mode, will ensure its retention.

I also expect the free rotor gyroscope to endure and anticipate that systems of about half the present weight will be giving close and accurate flight path control in both plan and height. In association with the appropriate sensors, the inertial navigator will be making possible really smooth and safe automatic landings, including guidance during roll out.

DISCUSSION

E. W. Pike (Regional Director — (United Kingdom) General Precision, Inc., Twickenham, Middlesex, England): Does Mr. Pateman think that strap-down inertial navigation systems have a future in commercial air transport navigation?

Mr. Pateman: There seems little doubt that strap-down systems in which the gyros and accelerometers are firmly anchored to the airframe, instead of being mounted in gimbals, can now be made to work.

The major impetus to this work has arisen from two factors. First, the availability of very powerful digital computers well able to accommodate the much more complex calculations involved in a strap-down system and, second, the possibility of laser gyroscopes being developed.

However, the development of such gyros to a standard acceptable to the civil airlines is likely to be a very expensive business and unless such develop-ment is paid for by governments on the military or space ticket, the amortisa-tion of development is likely to put the laser gyro out of court in terms of price.

It is perhaps worth noting that the accuracy at present attainable with gimballed systems is quite adequate and no great pressures exist for improve-ments in this direction.

However, large pressures exist to reduce the cost of ownership and to reduce size and weight and strap-down systems will succeed in the civil world, in my opinion, if they can be shown to make significant contributions to these factors.