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AUTOMATIC FLIGHT CONTROLS IN FIXED WING AIRCRAFT – THE FIRST 100 YEARS

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Automatic flight controls in fixed wing aircraft The first 100 years

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1. INTRODUCTION

In 1973, automatic flight controls is one of the most exacting fields of technology, requiring a balanced combination of art, science and human understanding, and the efforts of large project management teams backed by adequate resources to bring any new concept to fruition.

Today's systems derive almost entirely from the technology of the past 25 years, and hence it is little known that there was some activity in automatic flight control for fixed wing aircraft as long ago as 1873, some 30 years before the world-changing events at Kittyhawk and when mechanical flight was still confined to balloons and a few rudimentary gliders.

One century ago was still the era of lone inventors, rather than project management teams. It was a time when exceptional engineers and scientists could obtain a significant outcome from their own thinking and personal skills. It was a period when the world had just been given, largely as a result of the efforts of individuals, the telephone, typewriter and torpedo.

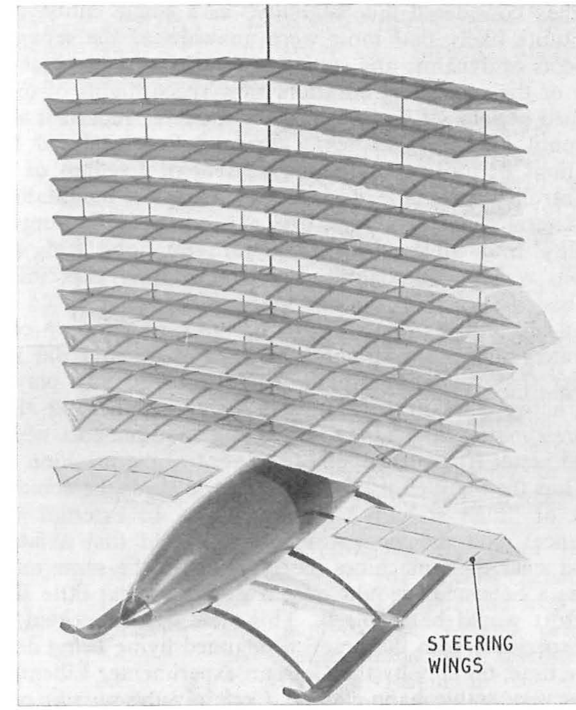
However, automatic controls engineering, like "mechanical flight" was in its infancy. To most people, problems of control and stability were confined to such things as remaining upright and in steady motion on a penny farthing bicycle. The most widely used control device was the steam engine speed governor. Gyroscopes had a recognised potential, but were, as yet, little more than scientific curiosities. Negative feedback had been known for 2000 years, but was little understood. Mathematical analysis was to some extent pursued for its own sake, and was little used by the great creative engineers like Edison. Indeed it was to be some 70 years before the work of the French mathematician Laplace was applied to the analysis of the stability of systems in such a manner that it became the everyday language of the controls engineer.

The centenaries of man's endeavours in many fields of science and engineering are rolling by and 1973 now marks 100 years of background on automatic flight controls for fixed wing aircraft.

It is the object of this paper to trace the evolution of the systems involved, concentrating mainly on the period from the beginning up to the end of the Second World War.

The last twenty-five years has seen vast activity on a very wide front which has been well documented. However, to give some perspective to the earlier work, some aspects of this recent history are covered, but these are restricted to topics of particular significance such as the impact of available technology, the development of the current generation of automatic landing systems and the first commercial supersonic system.

The original paper was presented to a joint meeting of the Royal Aeronautical Society and Institute of Electrical Engineers at 4 Hamilton Place on 18th October 1972.



(Musée de l'Air, Paris)
Figure 1. Renard Decaplane model.

2. EARLY HISTORY

In 1873, the Frenchman, Colonel Charles Renard tested from the St.-Eloi Tower near Arras an unmanned multiwing glider (decaplane) incorporating an automatic control device aimed at improving the machine's directional stability(1) (Fig. 1).

The automatic device comprised a transverse pendulum connected to operate differentially a pair of small rotatable wings. Colonel Renard's idea was that "if the aircraft leaned to one side at the beginning of a turn, the action of these small wings, one rising inside the turn and the other descending on the outside of the turn, would straighten the aircraft". Renard's machine was possibly the first on which an attempt was made to use an active stability device or "artificial stabiliser" and he was not to know that it was the forerunner of a range of similar devices and the first contribution to a new field of technology.

In fact the decaplane test was unsuccessful. It descended from the tower in a spiral dive and although the stabilising wings appeared to operate as expected, they were clearly unable to counteract the effect of the powerful lateral instability which was inherent in the design. (There appears to be anhedral on all ten wings.)

Today, Renard is considered by historians to have made his major contribution to aeronautics in the field of airships, and although his joint effort with Krebs to produce the first navigable airship "La France" was a significant milestone in aviation history, it is to be hoped that future historians will also give some prominence to his early invention in the field of automatic flight control.

For almost 30 years after Renard's decaplane, the main efforts to solve the problems of powered flight were based upon the assumption that machines should be sufficiently resistant to any disturbance to be able to maintain their flight path without the need for any significant intervention by the airman-pilot. The early inventors hoped to achieve this by designing their machines with the characteristics of high pendulosity, which they called at the time "high stability".

They considered this "stability" as a single entity, and it is quite likely that most were unaware of the separate elements of dynamic and static stability from their observations of the very short duration, slow speed flights of their manned gliders, or their unmanned models. Indeed it was not until 1911 that Professor Bryan[2] first analysed the equations of motion of the six degrees of freedom of an uncontrolled aeroplane, derived the concept of longitudinal and lateral flight dynamics, and expanded the concept of stability into an analysable set of equations with the various well known stability roots. The early experimenters had only a hazy concept of such details.

In addition, before the turn of the century, they concentrated mainly on straight and level flight and did not predict that the airman-pilot would subsequently play a very active part in control, especially in roll, and they underestimated the change in stability requirements which would result from his capability to control the machine.

Thus the main efforts were directed towards the achievement of "high stability" (i.e. resistance to external disturbance), and the view was generally held that aviators would steer their machines more or less in the same manner as a helmsman would steer a ship, and that little skill or effort would be required. This view was supported by the experience with the practical manned flying being done at the time, notably by the German experimenter Lilienthal in his very stable hang-gliders. Certainly the pursuit of a solution to the "stability" problem received as much attention, if not more, than the prime ones of getting adequate engines and aerodynamic lift.

There were two main schools of thought[3] as to how the so called high degree of "stability" could be achieved. One held that it could be made inherent in the basic design of the craft, on the lines of Cayley's concepts, while the other school argued that some "artificial" automatic control means would have to be furnished, akin to, as Lanchester later said, the "brain and nerve centres" of birds.

In 1891, according to a patent[4] in his name, the expatriate American inventor Sir Hiram Maxim gave serious consideration to the "artificial" approach. He described a steam powered aeroplane using pendulous gyroscopic stabilisation in pitch which was designed "for maintaining the ship on an even keel or any desired inclination".

By 1894 he had produced a full scale prototype machine and the first model of the stabiliser but he had it in mind to test the power/lift aspects and the stability/control aspects separately[5]. This is not an unreasonable approach, being comparable with that used for testing certain modern jet-lift VTOL designs.

His huge machine was therefore mounted on a railway track with restraining guard rails, and with full steam up it succeeded in lifting. Unfortunately it fouled the guard rails and was extensively damaged, which brought Maxim's activity to a close. The stabiliser was therefore never tested in anger, and an experiment which might have had a considerable impact on the early history of mechanical flight came to nothing.

Maxim's patent showed surprising sophistication. He proposed using a pendulously suspended gyroscope to operate an extensible link servo motor in the control cable runs, the whole system being driven by steam (Fig. 2). The device incorporated a pitch angle demand wheel, and also a speed vane which was connected via a curved slotted arm into the linkage between the gyroscope and servo-valve. This had the ability to give smooth automatic engagement of the gyroscopic control and a variable gearing as a function of airspeed. There was also a colour banded disc geared to the gyro wheel spindle to indicate its rotation.

The system therefore had all of the basic elements of a modern autopilot; a gravity erected pitch attitude sensor, a pilot's controller, a limited authority amplifying servo, parametric gain control, a failure indicator and an automatic engage synchroniser.

The intent behind Maxim's design is clear but at the time one of his assumptions about aeroplane flight characteristics was wrong.

Up to this time most of the experience with heavier-than-air machines was in gliding flight. Maxim tried to envisage the problems to be faced also in climbing flight, which he assumed would be divergently unstable. His patent says "A body moving quickly through the air is liable to very sudden and erratic movements. For instance, if a plane is moving forward through the air at a slight angle or inclination and at a high velocity, should the forward part of the plane become slightly tilted upward, the said plane will be lifted much more rapidly, and will also have a tendency to tip or tilt still further in the same direction. It is, therefore, very difficult to cause a plane to move straight through the air, especially when the said plane is inclined so as to cause it to rise in the air".

He therefore intended that the stabiliser should enable his machine to be held at a constant climb angle, as set into the control wheel. Unfortunately he then goes on to reveal that at the time his knowledge of flight dynamics near the stall was fallacious. He assumed that in the event of the engine stopping, the aeroplane would commence to travel backwards. This would reverse the pressure on the speed vane so as to demand via the slotted arm, a reversal of the pitch attitude which would cope with flight astern. His aeroplane design was almost symmetrical so perhaps he thought that a stable backward descent could be initiated; in fact in 1908 he wrote that his design arranged that "the lifting effect . . . was directly over the centre of gravity" which opens the way for some interesting speculation.

However Maxim's solution to the problem he envisaged was cleverly executed and quite valid. Indeed his whole autocontrol concept was far ahead of its time, and in detail his mechanical design is elegant to a degree which would be hard to match today. (One example is his servo rotary feedback rod, which abuts onto the pilot's demand unit, comprising a very clever implementation of a mechanical differential.)

Sir Hiram Maxim should rightly be credited with the invention and construction of the first practical attitude demand autopilot for aeroplanes and can be excused his early misconception about their flight characteristics, which a man of his genius would have corrected if his experiments had continued.

3. THE TURN OF THE CENTURY

Before 1900 the realisation began to dawn that the "high stability" aeroplane designs were not being matched by adequate control power, thereby resulting in a very poor manoeuvrability. Hence any upsets due to severe gusts or wander of the machine in flight resulting from its own lack of trim, could not always be corrected quickly enough. Indeed, it was almost certainly as a result of such limitations that Lilienthal, in 1896, met his death in one of his hang-gliders.

By the turn of the century the Wright Brothers in America had quietly proceeded someway down a different experimental route[6]. After studying the Lilienthal/Chanute/Pilcher principles and doing some experimental flying and wind tunnel work, they decided to design and build gliders with quite different characteristics from those of their predecessors. These were neutrally stable or unstable, especially in roll, having anhedral and a high cg, in which they lay prone instead of hanging suspended underneath. In these they experimented extensively with flying controls which would give them the ability quickly to counteract any disturbance. It is likely that the environment in which they experimented in the Kill Devil Hills, North Carolina, was much more gusty than the sites used by their European counterparts, and forced them to adopt this approach.

Their series of highly controllable gliders was followed with an engined machine and their first sustained powered flight at Kittyhawk on 17 December 1903 and their subsequent successes owed everything to their decision to produce machines with powerful controls which needed to be flown continuously, and to accept that the airman-pilot must accustom himself to playing an active role in the task of maintaining the required aircraft attitude.

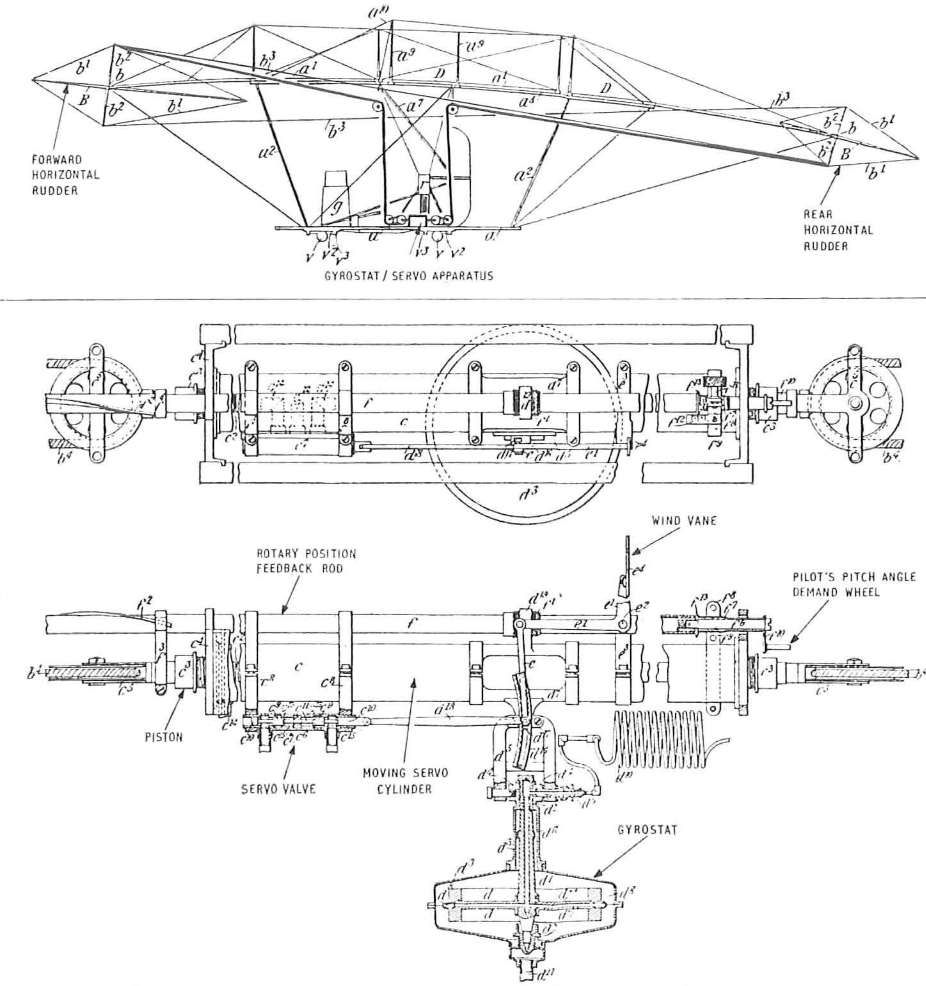


Figure 2. Maxim stabiliser.

The Wright Brothers also produced practical controls which divided the task of flying their machines between lateral (in their earliest machines the wing warping was coupled to rudder to offset "wing warp" drag) and longitudinal aspects, thus anticipating unknowingly the reasonable separation of lateral and longitudinal flight dynamics which Bryan later derived from a formal analytical approach.

4. AFTER KITTYHAWK

It would seem that by 1905 two severe blows had been struck against much of the work of the previous two decades. First, the concept of designing for high "stability" with limited controllability had been shown to be undesirable. Secondly, there seemed at first to be little need to continue the the pursuit of "artificial" stabilisers, as clearly the controllability of the unstable or neutrally stable Wright machines seemed adequate.

However, the latter point was by no means generally accepted, despite the fact that in 1905, the Wrights pressed home the success of their active piloting technique by completing more than 40 flights involving all of the necessary banking and turning manoeuvres required in "aerial navigation"[7]. Indeed, by modern handling standards the Wright Brothers would have worked quite hard and with considerable concentration to keep their "Flyers" under control. This was admitted by them in their private letters, and they may have considered the possibility of ultimately including some artificial stabilisation. The idea of exploiting their machine for both civil and military use was now in their minds, and if the ordinary man in a flying population could not have high stability in a basic design, he must certainly appear to have it in operation. On the military side, a German balloon official in 1907 remarked that "the Wright machine was more suitable for an acrobat than a soldier, as it carries only one man and he is far too busy looking after it than to attend to matters of war"[8]. This was not quite a fair statement, as shortly afterwards it was demonstrated to the US Signal Corps as suitable for army reconnaissance. However such comments no doubt worried the famous brothers and certainly the general European view was that the low "stability" of the Wright machine was a curious characteristic which ought to be eliminated.

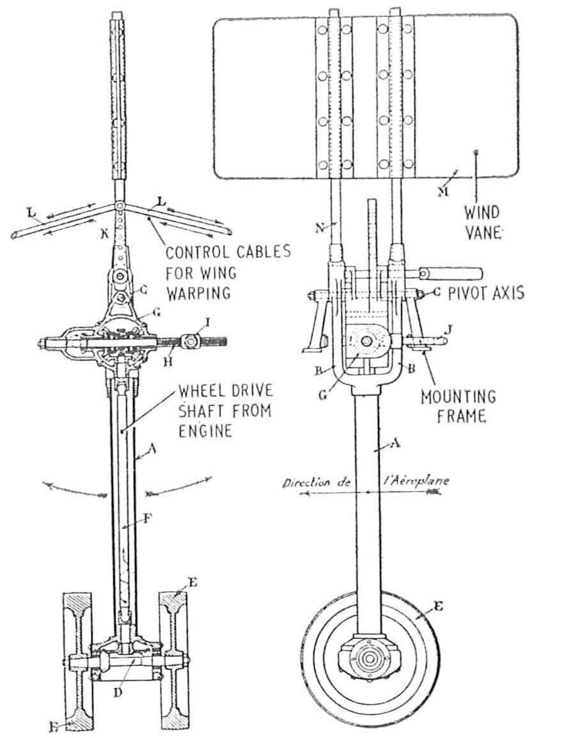
It is worth recalling the state-of-the-art in automatic controls and the general engineering environment at the time in which these early flying experiments were being made. Ships' stabilisers, employing heavy, direct reacting gyroscopes were available and in use and the ships' gyrocompass had been invented. Torpedoes had also undergone extensive development and these now used clockwork gyroscopes for course keeping. Louis Brennan and others were experimenting with monorail trains directly stabilised with heavy gyroscopes. Everything pointed towards an increase in the use of "artificial" devices to gain high stability.

The most extensive flying experience was with balloons and airships, which were also relatively stable, sedate and friendly, and heavier-than-air machines would certainly be expected to exhibit the same characteristics. It was argued by many that if artificial stabilisers were desirable in ships they would be essential in aeroplanes; perhaps more so because the "air-ocean" was more turbulent than the sea, and aeroplane "hulls" were less developed than ships' hulls.

Pursuing the line that the common man would soon have need for an aeroplane (rather like the Volkswagen concept), Stanley Beach, then aviation editor of the *Scientific American*, with some advice from Elmer Sperry, built over the period 1908–1910 an aircraft on the Blériot pattern with a large engine driven gyroscope suspended rigidily, spin axis vertical, beneath the forward fuselage[9]. This was intended to give automatic stability merely as a result of the gyro inertia. The wheel weighed 30 lb, a value suggested by Sperry. This may have provided sufficient angular momentum but the rigid mounting would have introduced severe cross coupling control problems—the aircraft would have tried to precess on applying control moments —roll motion inducing a gyroscopic pitching moment and pitch a rolling moment—this provided, of course, that these moments did not destroy its mounting structure or the delicate airframe. The use of gyroscopes in this direct way has always presented fundamental problems due to the disturbing moment and the resistance from the angular momentum of the wheel being at right angles. Apparently the gyro-equipped plane did fly, but only performed gradual movements and must have been nearly impossible to control.

It is difficult to believe that Elmer Sperry, who was said to have assisted Beach, and to have checked his calculations, could really have supported this design, but he did in fact publicly associate himself with this project. Sperry understood the action of gyroscopes very well by this time and in 1909 had made notes about the application of signalling gyroscopes to aeroplanes, although perhaps he did not understand the problem fully and may have considered at the time that it was not unreasonable to use a gyro merely to give a high inertia, which was one of the methods used to stabilise a rolling ship.

Between 1909 and 1911 in France, several inventors made experiments on the use of gyroscopic precession for the stabilisation of flying machines. The concept of Louis Marmonier[10, 11] was an improvement on that of Beach in that he combined the characteristics of a heavy engine-driven gyro and pendulum (Gyroscopic Pendulum) and connected the device with cables to "warp" the controlling surfaces (Fig. 3). The pendulum rod was pivoted so as to swing laterally. It had a sideways facing vane on top above the pivot and a large double wheel gyro as a bob weight, the spin axis being horizontal in the plane of the pendulum action. The pendulum was connected directly to the roll control cables so that it could operate these to correct roll disturbances, the gyroscopic inertia resisting frictional torques and giving a stability to the pendulum which could not be obtained with an ordinary bob weight. A yaw angle disturbance however would also cause a roll control operation, by inducing a gyro precessional torque. Whether or not this could be advantageous would require a detailed stability analysis, which would also depend upon the characteristics of the aircraft in which it was installed, although it was claimed by the inventor to be independent of this. Roll rate/yaw rate coupling is used



(Musée de l'Air, Paris)

Figure 3. Marmonier stabiliser: 1909.

in modern stabilisers but the success or otherwise of this action in the Marmonier device would depend a great deal on the details of its implementation. The effect of sideways gusting on the vane is also open to speculation. The first effect would seem to be to cause rolling moment via the cable connections but there would also be a yawing moment applied to the aircraft directly through the pendulum pivot, resulting from a gyro precessional torque. The details given of the device in the literature leave open some doubt as to whether even the basic dynamic problems involved were properly understood. What degree of success was achieved with this and similar devices is difficult to say, but they represented a further stage in attempts to use high inertia gyroscope controls.

At the other extreme Paul Regnard, also in France, proposed a small electrically driven vertical gyroscope which could close relay contacts to energise solenoids connected to the pitch and roll control surfaces. At best this system would have been an insensitive "bang-bang" device and no reports of flight testing have been discovered.

By 1909 numerous aeroplanes of different design were flying but none satisfied everybody's desires. Colonel Capper, Superintendent of the Government Balloon Department at Aldershot, England, commented at this time that "particular emphasis should be laid on the need for greater automatic stability in all heavier-than-air flying machines . . . and that inventors should aim rather at increasing automatic stability than at increasing speed"[12]. He probably had "inherent" rather than "artificial" stability in mind at the time, but certainly the protaganists of both schools of thought remained active and vociferous.

Although many of the artificial stability devices proposed in the early years of powered flight employed gyroscopes, there was considerable effort also expended in misguided attempts to get attitude information from a simple pendulum. A great deal of controversy surrounded their use, probably resulting from the earlier pendulous inherent stability concepts of the 1890s; but all such attempts

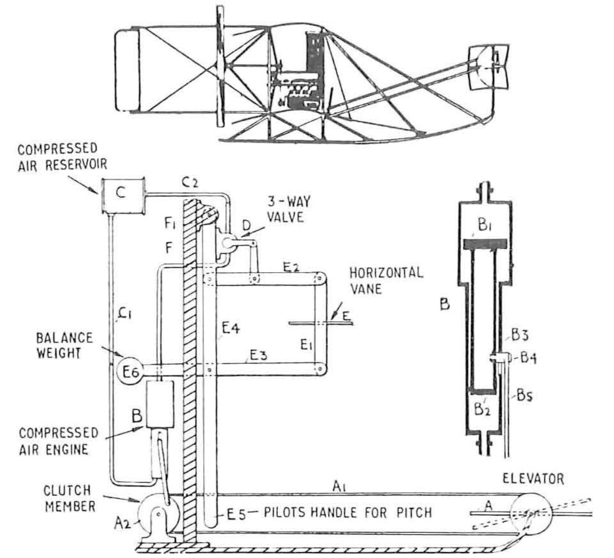


Figure 4. Wright stabiliser (pitch): 1909.

were destined to failure due to susceptibility to unwanted accelerations and poor damping. Some inventors undoubtedly used a damped pendulum in an acceptable role as a side force sensor, but it was never possible for such devices alone to solve the severe and complex problems which the automatic stabilisation of aeroplanes posed.

A number of the early pendulum devices were coupled with wind sensors of various types and such designs persisted or a long time, which seems to indicate that they served some useful purpose. They may have compensated for early design limitations, or been effective as vertical references to some extent due to the limited manoeuvre capability of the early machines.

Certainly in the underpowered machines of the day many pilots were rightly reluctant to perform any steeply banked manoeuvres.

There were numerous variations on this theme, from pendula coupled to controls to schemes in which engines and pilot were suspended, in underslung cradles, some having appropriate connecting cables or rods to the control surfaces. One such example was the Moreau "Aerostable"[13] in which this French inventor frequently flew himself "hands off" while target shooting! The Moreau machine had a cradle cockpit pivoted to swing freely and appropriately connected to the elevator and ailerons, so that it could be controlled by deliberate movements of the pilot. Its stability was also subject not only to apparent gravity, but also to air velocity, due to the drag of the cockpit area. There would also be a damping action from the control surfaces. It was therefore not really a simple control system.

The basic shortcomings of the simple pendulum operated "stabilisers" however undoubtedly enhanced the determination of many airmen to oppose the use of all artificial stability devices, while urging the automatic controls designers to produce something better. There is no doubt that the problem of stability exercised the minds of everybody in the field.

A number of very sophisticated stabiliser designs employing power amplification were also pursued in the early years; the activity of Franz Drexler in Germany in 1909 was particularly noteworthy[11] for his mechanical and electrical ingenuity. Drexler was a naval hydraulics expert who first attempted to harness pendulum sensors to hydraulic servos connected to the appropriate steering wires. His system was heavy, and inevitably he ran into the expected shortcomings of pendula during flight testing which quickly led him to replace them with gyros. They had relatively advanced electrical signal detection similar to the Renard concept.

The pressure of all of this activity finally spurred some parallel action from the Wright Brothers and the magazine *Flight* for 10th July 1909[15] records that: "Bearing in mind that the Wright Brothers have invariably in their public utterances given voice to the opinion that learning to fly was more or less like learning to ride a bicycle, and that a flyer had no more need for automatic stability than such a machine, it may possibly surprise a good many of our readers to learn that the Wrights have applied for a Patent (No 2913 of 1909) to protect a system which is calculated to render their flyer automatically stable in the air".

The Wright Patent covered the actuation by compressed air of the flying surfaces under the control of a "pivoted vane acting under the influence of wind pressure for pitch control (Fig. 4), and a pendulum for lateral control". The pneumatic actuators had no position feedback so the system relied upon aircraft motion to null the demands from the sensors. The automatic controls were meant to hold the aeroplane in whatever condition was demanded by the position of the pilot's levers, pitch control being a function of incidence and roll control a function of the pendulum action. The sensors and control surfaces operated so as to reflect no movement into the pilot's levers, a very advanced idea at the time.

The Wrights thought that the vane would be "constantly jogging up and down" and their description of the pendulum control in the original patent application indicated that, like many others, they thought it would measure roll attitude. (It was reported in 1914 that the system had been under test for some time and that "a system of electrical contacts is employed which counteracts the inherent deficiencies of the pendulum . . . .") The stabiliser seemed to be of special interest to Orville Wright, and in 1914 he was awarded the Collier Trophy, probably for the year 1913, in recognition of his work on it. (Wilbur died in 1912.)

The use of the pendulum and the controversy surrounding it was in time to be eclipsed by the invention and proper use of satisfactory airborne gyro-sensors, and incidence or speed vanes were to survive only temporarily as safety devices, because of the low power of early aeroplanes and the difficulty of maintaining adequate speed margins over the stall. The need for automatic speed control in early machines was outlined by Mervyn O'Gorman in a paper to the Royal Aeronautical Society in 1913[16]. He supported his opinion with airspeed and altitude recordings from an early instrumented test flight at the Royal Aircraft Factory, of which he was then Superintendent. Figure 5 shows how the airspeed was around 30 mph at take-off, settled out at 55–60 mph in the climb and peaked at around 70 mph in the descent. In level flight at 100 ft there were rapid excursions of 5–7 mph on a day described as calm.

A number of devices were invented to tackle this problem, apart from the Wright one already mentioned. Budig, Etévé and Doutre were active on this in the 1912–1914 period. The Doutre Speed Maintainer[17] of 1912 is representative and is what today we would call a stick-pusher. This ensured that an aeroplane's nose would be depressed if a fall in speed occurred for any reason. It was an ingenious device (Fig. 6). It weighed 44 lb and was similar in effect to the Wright incidence vane control except that the wind vane was at right angles to the direction of flight and normally inactive against a spring and an abutment, unless the airspeed dropped below the safe level. In this case a pneumatic servo operated to depress the elevator,

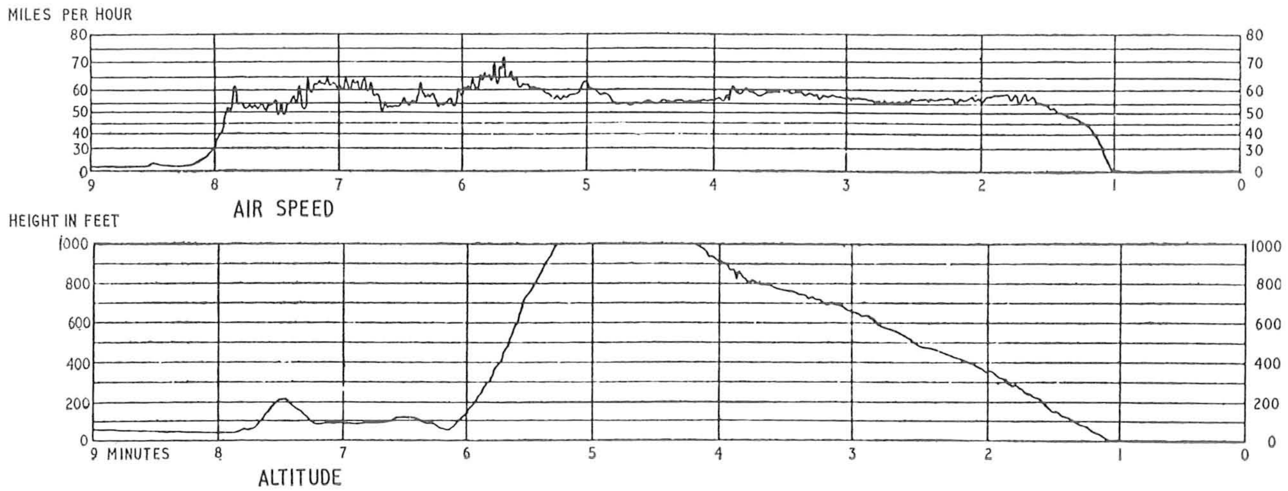


Figure 5. Airspeed and altitude recordings: 1913.

which was indicated to the pilot by the movement of his control stick. The vane action was also damped by spring restrained moving weights, which formed in effect a longitudinal accelerometer. The device was fully demonstrated in a Maurice Farman biplane, piloted by M. Didier.

It was not until well into the First World War that better engines and machines allowed cruise speeds to increase to the region of 100 mph which was sufficiently remote from the stall to remove the immediate interest in such protection.

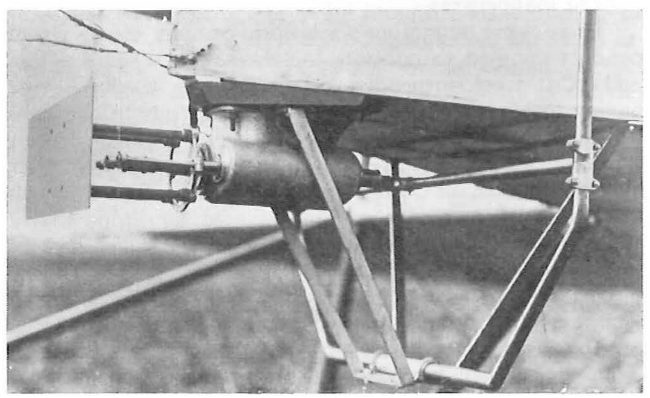
By 1913, all manner of aeroplanes were flying which made no use whatsoever of any artificial (automatic) stabilisation devices. However, the need for pilots to be highly skilful and agile was still by no means generally accepted and various ideas for improving stability (and safety), were continually being pursued. In fact during 1912 a most significant development had commenced in New York. The Sperry Gyroscope Co. had again turned its attention to the problem of aeroplane artificial stability, and late in the year a gyroscopic stabiliser (lateral only at the time) was installed in a Glenn Curtiss float plane and flown for some minutes without any pilot intervention[18]. Lawrence Sperry, 18 year-old son of the founder of the Sperry Company, flew as the test engineer.

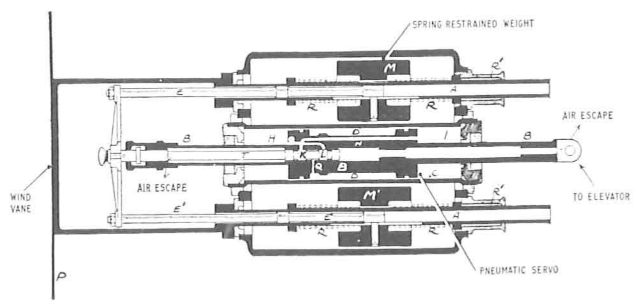
However, a Mr. Earle Ovington writes in 1912 from the viewpoint of an "experienced aviator"[19]: "I believe that the future of the aeroplane rests in the solution, among other things, of the problem of lateral stability. But I do not think that an automatic mechanism is what is wanted to accomplish the purpose . . . but . . . inherent stability in which the machine is constructed in such a manner as to maintain its stability under all conditions . . . As an aviator, I much prefer to trust my life to my own brain and muscles than to trust it to any automatic device, and I believe that most aviators are of the same opinion. The men who are spending so much time inventing more or less complicated devices for maintaining automatic lateral stability in aeroplanes are largely those who belong to the 'rocking chair fleet' of aviators. In most cases they are not practical flyers. I would hate personally to get into a machine and realise that if a certain automatic device did not operate I would surely be killed".

Then, from T. W. K. Clarke, also in 1912[20] the opposite view: "I look upon automatic apparatus as not so much a means of completely relieving the pilot of the responsibility of the (say) lateral control, as giving him something which can perform for him the greater portion of the physical effort involved, thus conserving his energy, and leaving him more prepared to meet circumstances requiring steadiness of mind and body. Even with complete failure of the apparatus, such an automatically controlled machine becomes merely an ordinary hand operated one". So the arguments raged.

Then, in 1913, a blow was struck for the inherent stability approach which set the main course for the future. Controlled aerobatics entered the scene. The most widely publicised were performed in France by Adolphe Pégoud at Juvisy and Buc in September[21]. He used a specially strengthened Bleriot monoplane and his original intention was "to demonstrate recovery capability from unusual attitudes". However his inverted flying and loops prophetically indicated the possibility of complete mastery, by skilled pilots, of controlled manoeuvres which could never be performed by any automatic controls then contemplated. Pégoud repeated his feats soon afterwards at Brooklands. Two months later B. C. Hucks, who earned his living as a display pilot, became the first Englishman to perform aerobatics.

The stage was now set for a series of inherently stable but eminently controllable aeroplane designs which would have no essential need for artificial stabilisation. Such machines would dominate the skies of France later in the war which was to start within a year.





(Flight International)

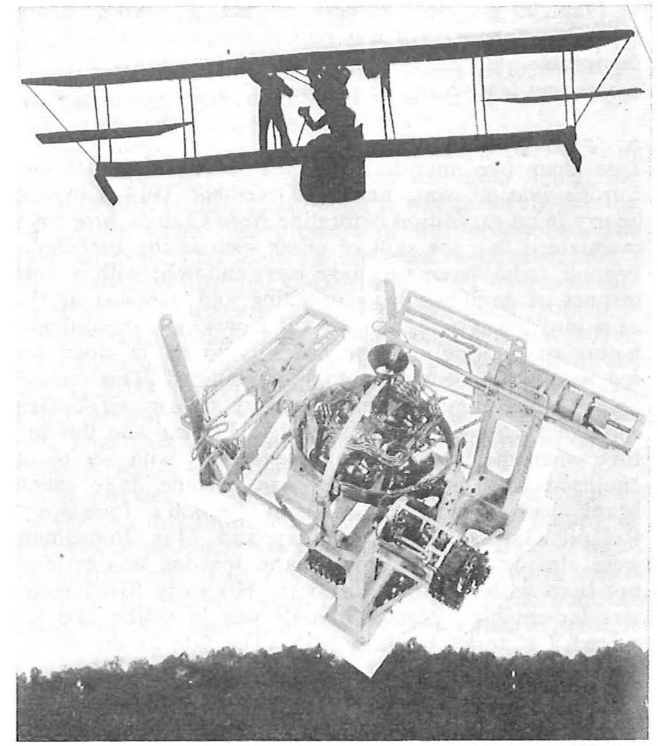
Figure 6. Doutre speed maintainer: 1912.

5. LAWRENCE SPERRY

On June 18, 1914, in what would seem, for some time, to be a parting gesture by the "automatics" school, the scene was lit by a veritable super-nova of engineering skill and practical accomplishment. Although the development of aeroplane automatic controls would almost cease for the next decade, there occurred an event which would later determine the course of their development for aircraft right up to the present time. On this day Lawrence Sperry demonstrated from the Seine at Bezons the fully automatically stabilised Curtiss flying boat which the Sperrys had been developing for several years[22]. The machine was entered for the aeroplane safety competition (Le Concours de la Sécurité en Aéroplane) which the Aero Club of France was conducting on behalf of the French War Department. The demonstrations were preceded by elaborate but lucid press releases and were arranged to give the most dramatic impact, which later included taking several judges on flights. The Sperry Gyroscope Co. was awarded the top prize (400,000 francs; at the time £2000 or $10 000 which covered the $8000 which it had cost the Sperry Gyroscope Co. to develop the stabiliser). During the demonstration the judges and spectators were treated to the sight of the aeroplane flying steadily at low level under automatic control with Lawrence Sperry standing in the cockpit, holding his hands above his head, and his French mechanic, Emile Cachin walking on a wing (Fig. 7).

The system used by Sperry was a very elegant piece of engineering and weighed about 40 lb, less than the simpler Doutre Speed Maintainer. Like the Doutre device, it was also primarily a mechanical/pneumatic system, and used electricity (ac generator) only to drive the gyro wheels. It had two axes of control, roll and pitch, the attitude sensing in each axis comprising a pair of counter-rotating gyros (each weighing 2 lb and driven at 12 000 rpm) with gimbals coupled mechanically so that precession torques were always in equal opposition. All spin axes were horizontal and each pair of gyros was pendulously suspended in gimbals, the whole being nested on a single platform. This was the first aircraft gyro stabilised platform in the form accepted today. Pitch and roll attitude errors operated mechanical roller switches which in turn actuated pneumatic servos to move respectively the elevators and ailerons, the switch operations being cancelled by mechanical position feedback from the control surfaces. The feedback mechanism used was described by Sperry as an "easing off" device to prevent over-oscillation. There was also a so-called "force-impressor" to offset erection to a false vertical during turns.

A multi-purpose anemometer between the wings measured airspeed which was used to provide a stall protection (a "vol plané" demand for 20° nose down) similar to the French Doutre device, and in addition the airspeed reading was used "to move the fulcrum of the plane's control levers so that the resulting angles of the ailerons or elevator suited the speed of the aeroplane". This must surely have been the first actual use of parametric gain control, although Maxim had such a provision implicit in his design of 1891. (Elmer Sperry was an avid reader of patent specifications and it is interesting to speculate as to whether he ever studied the Maxim claims).



(John Hopkins University Press)

Figure 7. Lawrence Sperry stabiliser demonstration: Paris 1914.

Other experimenters had proposed the use of signalling gyroscopes before Sperry. By 1911, Drexler in Germany had progressed his earlier design to the stage of using potentiometer pick-offs on a gyro which could drive electrohydraulic servos, a more sophisticated approach, but to Lawrence Sperry undoubtedly goes the honour of bringing the first system up to a practicable demonstratable standard.

The Sperrys refused to sell their systems to the excited Continentals, despite handsome offers of large orders from Germany in particular. It was in keeping with Elmer Sperry's principles not to supply his inventions to anyone if he did not consider they had reached an adequate state of development. He had had unfortunate experiences in this respect with his ships' stabiliser in Germany, and in the case of the aeroplane stabiliser he was particularly concerned about the unreliability of the pneumatic servos and wanted to replace them with electrical ones.

Certainly the 1914 Sperry aeroplane stabiliser had many problems, although it had been under development for several years. A great deal of effort was needed to set it up for each flight, and by today's standards it was a touchy device that needed constant adjustment. Indeed Sperry had to contend with difficulties similar to those on today's systems, but without the solutions engineers now have at their disposal. His gyros had a relatively high free drift rate, and therefore had to be made pendulous and hence sensitive to unwanted disturbance. Other problems were friction in gimbal bearings, deadspace and flexibility in the control wires and airframe and because of the unavailability of proportional amplifiers and devices for mixing input signals, his complete system would have been, by modern standards, very difficult to adjust and optimise.

Nevertheless, the success of the Lawrence Sperry demonstration of 1914 was remarkable, and the wide and favourable publicity which attended his efforts over the succeeding few years was justified.

6. FIRST WORLD WAR

Less than two months after the Bezon demonstration Europe was at war, and in December 1914 Lawrence Sperry in an exposition before the Aero Club of America[23] maintained that the skill of pilots such as the Frenchman Pégoud, (who "seems to have been endowed with a super instinct of equilibrium as unfailing and unerring as that of a bird") was rare, and even if it was not, the fatiguing nature of piloting and the necessity to fly in cloud and fog would still demand automatic stability. This remarkable young man was certainly very convincing because early in 1916 he sold 40 systems to France, and this at a time when the first air-to-air "dog-fights" with aeroplanes equipped with machine guns had become daily events. Many had in fact followed in Pégoud's footsteps[24]; Roland Garros, Major Hawker and Max Immelmann were already famous. Immelmann for one was certainly not born with a "super instinct". His early flying record was lamentable. Pégoud himself was in action and had scored 8 victories by July 1915. The fate of the 40 systems was inevitable. After some desultory tests the French announced that the stabilisers were too heavy, and in any case reduced the manoeuvrability which was essential for survival in combat. (The French had by this time become very disenchanted with high stability, whether artificial or inherent. They had been losing large numbers of their lumbering Voisin bombers to the enemy due to its lack of manoeuvrability.)

Following this, and through to the end of the War in 1918, automatic controls played no part in practical aeroplane designs for any purpose as far as can be discovered. In contrast a proliferation of designs and vast experience accrued in basic aerodynamic, structural and engine designs and in the art of piloting.

In particular, the designers and mathematicians at the Royal Aircraft Factory and National Physical Laboratories[25] had been making good use of the analytical work done in 1911 by Professor Bryan. One outcome was the BE2c of 1913, which could be flown "hands off" for long distances in calm conditions. Dr. R. T. Glazebrook (later Sir Richard Glazebrook), Director of NPL told the Royal Institution early in 1915[26] "that the high degree of stability of the British aeroplanes now used in the war had been secured by measuring forces that deflected the machine and by securing complete control for the pilot through the exact adjustment of the rudder, the vertical fins, and the form of the wings, which might be flexible or fitted with movable flaps to resist pressure in certain directions. While stability depended much on the skill of the pilot, the skill required was much diminished in a stable machine. Automatic stability based on gyrostatic and other aids had not proved satisfactory, but inherent stability was attained through bringing counteracting forces to bear against gusts and removing factors causing oscillation."

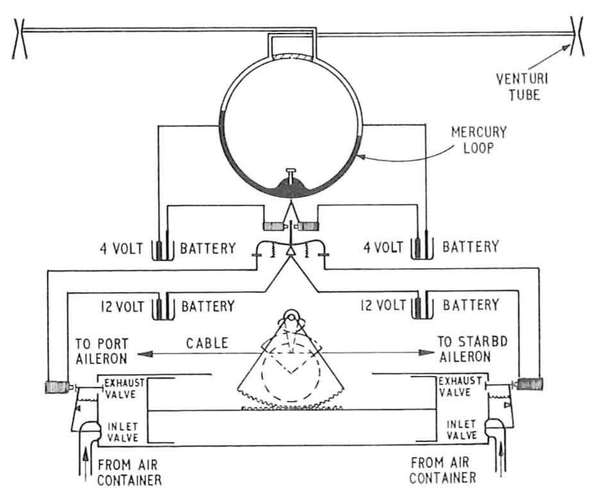
However, despite such assertions, experimental design work on automatic flight controls still continued, albeit on a limited basis. In the USA the Sperry Curtiss demonstrator could by now perform complete flights from take-off to landing under automatic control. Lawrence Sperry's confidence seems to have overwhelmed the passengers carried in his demonstrations as they were frequently induced into doing the "wing walking" stunt in order to remove any doubts they might have about the stabiliser's effectiveness.

On occasions the high-spirited Lawrence appeared to pay scant heed to the possibility of dangerous malfunctions. Although he had a foot pedal installed for instant disconnect of his stabiliser in anticipation of such problems he was not always quick enough or even ready to operate it. One report tells of Lawrence and a passenger making "a long flight sitting on the edge of the boat practically all the way".[27] Another story[28] is told of an occasion when, "bored by office routine, he took one of New York's glamorous young society matrons flying over Long Island Sound. Lawrence, who never lost an opportunity to demonstrate the dramatic uses of technology, activated the stabiliser . . . . but . . . unfortunately the machine malfunctioned, and the plane plunged into the bay". Lawrence was once described by a friend as "a real genius, a terribly hard worker, and equally strenuous in his leisure".[29]

Lawrence Sperry continued his developments through to 1917 when America entered the war, but at this time diverted his efforts to the design of a so-called "aerial torpedo" which was intended to perform much the same task as the German V1 did in the latter part of the Second World War. The automatic controls required were a logical development of his 1914 stabiliser, involving a change to electrical switches on the gyros to operate the servos and the addition of a barometric height control and a directional gyro steering system. The latter was inspired by some work Lawrence Sperry did on telescopic bombsights at Upavon in England in late 1914.[30] Distance on the aerial torpedo was to be obtained from a calibrated revolution counter on the propeller shaft and "at the exact moment it would operate to dive the plane into its destination at a tremendous speed".

These additions to the basic stabiliser during the First World War, especially the automatic steering, added new dimensions to aeroplane control capability. They were now not only artificial stabilisers, but became what the world would ultimately call "automatic pilots". (They were first called "gyropilots" by Sperry.)

Although during that war there was little development of automatic flight control devices, apart from the Sperry pilotless bomb system, in 1916 Mr. D. T. Glass-Hooper felt sufficiently motivated to write to *Flight* magazine[31] to propose in a long article a system for the "Electric Control of Large Aeroplanes". Mr. Glass-Hooper anticipated the current concept of "electrical signalling" by 50 years and made some interesting engineering proposals. His idea was to operate the control surfaces from solenoid devices, the current being provided from a battery and generator combination, the generator normally being driven from the aeroplane engine, or in the event of its failure, from an auxiliary propeller. He thus covered several dissimilar failure possibilities. The control levers were to move over arcs of contacts to regulate the currents to the solenoids and the absence of "feel" was to be substituted by observing the current readings on easily seen ammeters! Some of his claims for the system might be received sympathetically today. For example "increased space in the pilot's cockpit owing to absence of large and cumbersome mechanical controls". On the other hand credibility wavers at "as to the breaking of the circuits accidently, by an (electrical) wire snapping, or some such reason, it is a contingency so unlikely as to be hardly worth consideration!"



(Flight International)

Figure 8. Aveline stabiliser: 1921.

One problem of piloting which would later become very important to automatic flight control was that of flying through cloud.

Captain B. C. Hucks told the Royal Aeronautical Society on June 6th, 1917[32] that "there have been a large number of fatal accidents during the last three years entirely due to flying through clouds". Cloud flying at this time was performed by entering in a straight and level and trimmed condition, preferably flying south, and then applying the minutest corrections, as necessary, on the basis of magnetic compass and airspeed deviation. (Because of the effect of compass turning error, it is easier to hold heading when flying in a southerly direction, as the errors indicated are then of the right sign.) The bubble sideslip indicator was considered to be of little help. It is obvious that, with even the mildest turbulence, both airspeed and compass instruments would develop considerable excursions and the situation could soon get out of hand. When it is recalled also that spin recovery technique was barely standardised at this time, the magnitude of losses incurred was understandable.

Around this time, at the Royal Aircraft Factory, S. Keith-Lucas[33] was developing a highly damped magnetic compass (the "spherical compass"). This was a considerable improvement over existing types, but Captain Hucks said "what I want to see fitted is an instrument which will show a constant vertical or horizontal line and be independent of centrifugal force". (Captain Hucks, the first Englishman to "loop-the-loop" and the inventor of the Huck's Starter, survived wartime operations but died of influenza the day before the Armistice.)

In fact the instrument Hucks required was an Artificial Horizon. One was under development by the Sperry engineers at the time but was abandoned in 1918, not because of the cessation of hostilities, but because they could not get a free gyro device to work satisfactorily as a pilot's instrument in severe manoeuvring flight, although they had made successful use of it as an automatic controls sensor for relatively steady flight[34].

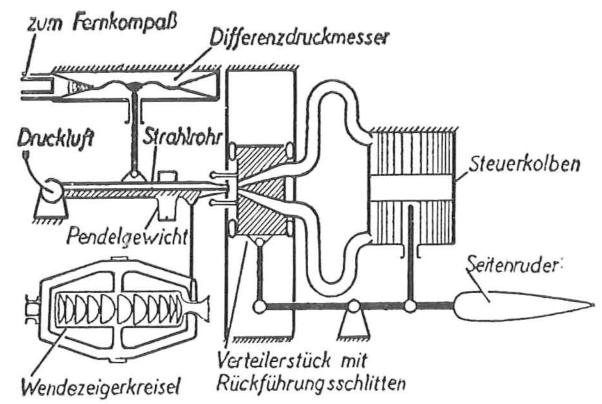


Figure 9. Askania air jet amplifier with gyro damping: *circa* 1926.

However the Sperry Co. did succeed, at that time, in producing the next best instrument for blind flying, the rate gyro turn indicator, although it was probably not the first on the scene. The pressure of war probably urged Germany to the first solution, attributed to Drexler, which was a combined turn and slip instrument. (This was in service in 1917 in large aircraft such as the giant Gotha.) It weighed 7·5 kg, including its separate small airscrew driven generator which supplied three phase power to drive the wheel at 20 000 rpm. This instrument was later licensed and further developed by the Pioneer Instrument Co. of New York, later to become the Eclipse-Pioneer Division of the Bendix Aviation Corporation.

The Drexler turn and slip development involved incidentally, the invention of the "rate gyro", thus putting in the hands of designers a practical device which could measure angular rate. This was an important invention which was later to become vital in automatic flight controls technology. The same can be said of another significant technological outcome of the last war in Germany, which was a series of remote reading magnetic compasses (the "Selen" compasses) developed by G. Wünsch at the Carl Bamberg factory[35]. The Selen compass was a startling development for the time, making use of the shielding of selenium photo-cells by a magnetic compass needle to generate an electrical output, presumably to operate a galvanometer indicator.

7. THE 1920s

In the years immediately following the Great War little actual work was done on automatic flight controls, although a new awareness of the need for "pilot assist" devices was arising from various sources, notably from the experience of aviators attempting fatiguing long distance flights. Alcock and Brown completed the first non-stop crossing of the Atlantic in a Vickers Vimy in mid-June 1919. At the end of the same year Ross Smith and his crew flew a Vimy 11 000 miles from England to Australia, which took almost a month. There followed a host of transoceanic and transcontinental distance and endurance flights in various countries, and there were almost daily reports of mental and physical strain endured by pilots in carrying out their control and navigation tasks.

By modern standards, aeroplanes were still difficult to handle and early in the 1920s there arose again a series of "simple" automatic stabiliser inventions, many of them being resurrections of the early pendulum ideas. An interesting, if not representative example, again from the ubiquitous French, was that of Georges Aveline, which was extensively tested by Messrs. Handley Page in England.[36] In principle it was another variation on the theme of pendulum control, although it took the form of a loop of mercury, the movement of which could close electrical contacts to operate pneumatic servos. The important new feature was that venturi tubes were fitted to the wing tips and tail and connected into the mercury chambers, so as to give "a counteracting action against the centrifugal forces which would normally upset the readings of a pendulum control" (Fig. 8). Unbelievers could be influenced by the likeness to "birds ears and their highly developed semi-circular canals". It was never completely established whether the system could be adequately adjusted for everyday use, although the pilot was presented with various controls and gain adjustments to assist with the setting up for any particular flight. The reports on flight testing of the device also pass quickly over the problems presented by gusts. Georges Aveline claimed that the system was superior to the Sperry gyroscopic one, although it was considerably heavier and lacked the finesse of control possible with a gyroscopically based system.

The Aveline device, and other contemporary inventions, were important indications of a new upsurge in interest in automatic controls, both for minimising the fatigue of long distance flying, and also perhaps, to overcome the shortcomings in stability of the aircraft of the time.

However, many of the developments which arose in the early 1920s were of little use and nothing came into being which was significantly better than the Sperry 1914–16 systems. Indeed there was never to be a completely new concept to supersede that of Sperry, and it was improved reliability and new technology which were to be the features of automatic control development in the future. Historians will no doubt give Lawrence Sperry the principal credit for the early practical development of automatic flight controls. (Lawrence Sperry died on 13th December, 1923 as a result of a forced landing in the English Channel.)

The mid 1920s marked the period when a number of large companies, and governments, turned their attention to automatic flight controls as a potential commercial business, or defence necessity, as the case might be, as distinct from a field of mere technical interest.

In England the Royal Aircraft Establishment began research on simple automatic controls, and in 1923 conducted the first automatic landing experiments since the pre-war activity of Lawrence Sperry. There had been other claims that automatic landings had been done since the war and in France, Moreau, probably in his "Aerostable", did a "no hands" landing and announced that "the invention was being developed with a view to its ultimate employment in commercial aviation"[37]. As the pivoted pendulous cockpit of the "Aerostable" was geared to the aircraft elevator, Moreau could exercise some control by moving his weight, hence his claim to have done "automatic" landing is frivolous. Sperry had certainly made landings by manipulating the special control stick of his automatic stabiliser, as distinct from the main pilot's controls.

The RAE activity arose from the desire of F. W. Meredith to test a theory he had proposed that "a quarter of a phugoid oscillation could produce simultaneously horizontal motion, stalling speed, and contact with the ground, if in a gliding approach the manoeuvre were initiated at a precalculated height and a prescribed airspeed, the said airspeed in fact being about 19% above stalling speed for several different types of aircraft[38]. Small errors could be tolerated according to calculation, without the resulting landing being in any respect heavy".

A Vickers Vimy was chosen as the potential test vehicle and the proposal was that the aircraft should first be held at an appropriate steady glide speed and in a suitable attitude for approach and then trimmed tail heavy. Following this a ground indicator, consisting of a weight on a line, would be lowered to a fixed distance below the aircraft. When the weight touched the ground it would be seen by the observer who would signal to the pilot to release the control column so that the tail heavy trim condition would then prevail, the phugoid would be excited, and the Vimy would land itself.

The RAE pilots were at first unimpressed by the theory. However one evening there was a long discussion about its merits, resulting in a disagreement, the outcome of which was that Meredith acquired a "bold" candidate to fly the Vimy.

The following day honour demanded that the test be conducted. It was successful and Meredith was pleased that his theory was correct. He observed the result from the front gunner's cockpit! This idea was also used later in an *ad hoc* way for assisting the landing of flying boats on glassy misty surfaces, when neither the landing run or horizon could be adequately seen. The indicator used was the retractable radio aerial cable.

In Germany during this period both the government and industry were assembling teams of engineers and scientists to progress the design of the basic elements of airborne automatic control systems.

Remote reading sensor developments were always of considerable interest to the autocontrols designer. Wünsch in Germany, in 1924, developed a successor to the remote reading "Selen" compass, which had a limited accuracy. The new compass employed a pickoff which measured course error pneumatically at the magnetic head. Amplification of the course error pneumatic signal was also achieved by means of another Wünsch invention, the moving air jet[39], which could give amplifications of 100 000 to 500 000 to feed robust remote reading instruments giving a magnetic heading accuracy of $\pm\frac{1}{2}°$. Again the development of a new instrument was quickly followed by a "coupler" to operate automatic controls. (The air jet or "Strahlrohr" was a very significant step in the history of automatic controls as it introduced high gain linear, or near linear, power amplification.)

Later in the 1920s these inventions were exploited further in the German Askania works, and this led to the development of a series of pneumatic course controllers, the first practical German autopilots[40]. It was around 1925 that Dr. W. Möller joined Askania to lead this work and over a period up to 1939 he was heavily involved in much of the development of Askania and Patin automatic systems, both in Askania and during an intermediate period when he worked at the government test establishment at Rechlin. Dr. Möller introduced the principle of using a restrained gyroscope (measuring yaw rate about the aircraft vertical axis) in conjunction with the pneumatic compass to achieve an accurate and well damped course control (Fig. 9). The gyro was in fact "restrained" as a result of the reaction forces of the air jet and the requirement for the yaw rate input (which incidentally was force added to the compass input) was to minimise banking errors from the magnetic compass. In some cases a pendulum monitor was also added to correct any inadvertent tendency for the aircraft to hold in a steady forward slip condition, which would have resulted in an incorrect track.

German industry and governmental establishments repeatedly tackled the problem of deriving signals from magnetic compasses for remote use, and their resulting expertise was to play an important part in their automatic controls accomplishments through to the end of the Second World War.

About the some time in France, Louis Marmonier, after 20 years of background in automatic controls, developed a complex mechanical/pneumatic automatic control system[41] operated from forward and lateral wind vanes and a platform of four restrained gyros (Fig. 10). The system was completely integrated with the pilot's controls, and was meant to be a package around which any aircraft could be designed. It was a magnificent piece of mechanical engineering[42], remarkably similar in concept to the Sperry 1914 stabiliser but with several very advanced additional features such as automatic failure diagnosis and

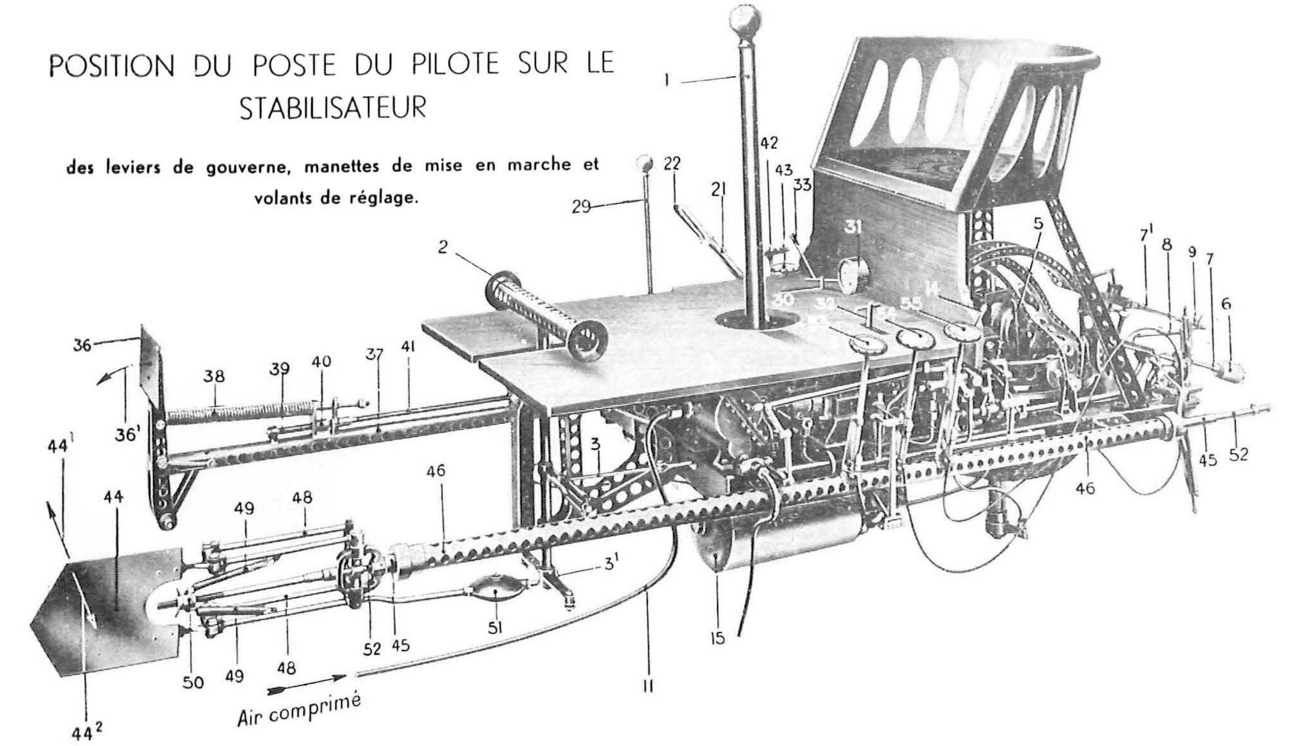


Figure 10. Marmonier stabiliser system: 1930–1932.

disengagement accompanied by the blowing of a whistle to alert the pilot. It is not known whether any flight testing of this system was ever conducted.

By 1925 the RAE, under the guidance of R. McKinnon Wood, was developing a pilotless aeroplane for use as a gunnery target. The concepts were used in various radio-controlled machines, notably the Larynx and Queen Bee. The RAE was therefore faced with the need to solve the total problem of automatic control from take-off to landing (or destruction). This was really the time when the RAE started serious work on designs which were to lead up to the first British autopilots. They chose as their basic approach the established method of stabilising aircraft attitudes by using free-gyros. This involved solving the problem, also previously tackled by Sperry, of using the gyros for active control in turning flight, while at the same time stopping them from developing unacceptable gimballing errors, or from becoming too affected by unwanted cross couplings.

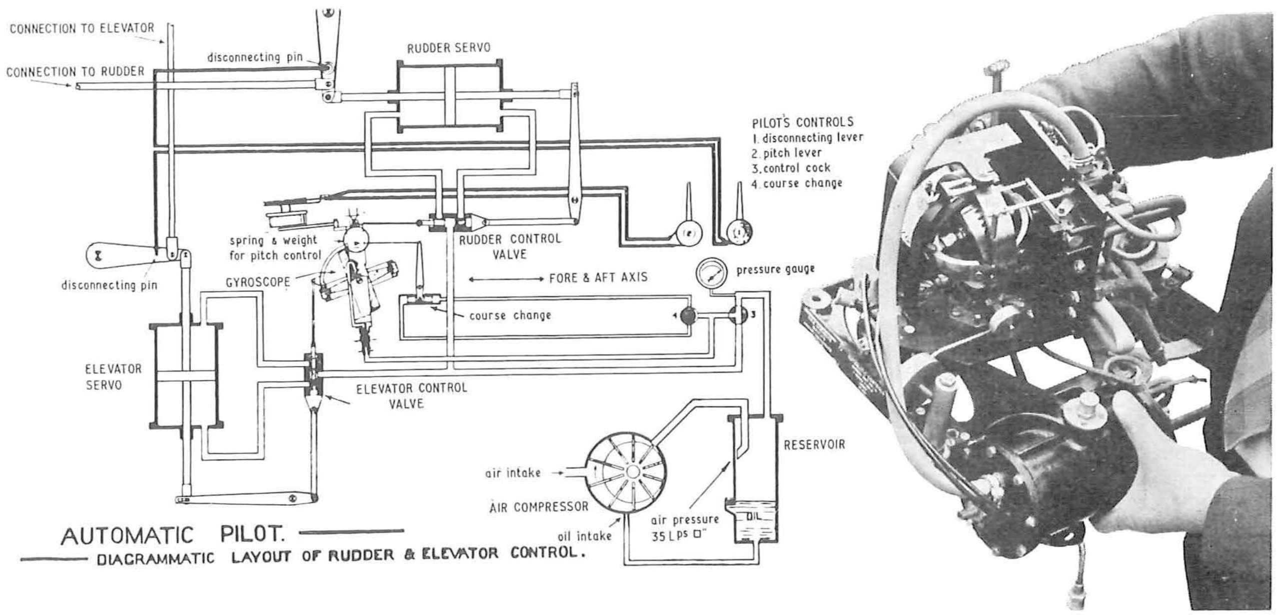
8. THE 1930s

The final outcome of this early work on pilotless aeroplanes was the RAE Mark I control[43], a proportional attitude command autopilot, later to be taken up commercially by Smiths after flight testing in a Vickers Virginia.

The system comprised basically two packages, each incorporating airdriven gyros, pneumatic valves and servos. One package handled rudder and elevator control, and the other aileron control. The system concept was simple, as can be seen from a study of one of these packages (Fig. 11). By today's standards, the gyro arrangement is curious. There are a number of ways in which roll, pitch and azimuth angles can be derived using two free gyros, each having two gimbals. The modern method is to use one gyro as a directional gyro devoted to azimuth only (this leaves a redundant gimbal). The other gyro is used as a vertical gyro devoted to roll and pitch. This arrangement gives the capability of 360° freedom in azimuth and roll with minimum cross-coupling effect.

The Mark I used instead a tilted pitch/azimuth gyro and a separate gyro roll. The idea of this was to enable roll and pitch verticality monitoring to be optimised separately. This enhanced the capability of the system in the performance of gentle unbanked turns without having to cope with the problem of slow erection of a vertical roll/pitch gyro to a false vertical. This is important in making turns for the purpose of correcting course for bomb aiming and photographic survey work. Course and elevation was controlled by precessing the appropriate gyro gimbal. For course changes this was done by operating a compressed air valve which applied a torque to the inner (pitch) ring of the gyroscope. Elevation changes were made by unbalancing a spring weight constraint, applied via a wheel roller on the azimuth gimbal. A clever engage interlock ensured that the servos were bypassed, and hence controls were unlocked if the gyros were not running or if the aircraft attempted to take off with the autopilot engaged. In the interests of safety there was also an elevator servo torque limit cut-out.

The optimisation of the Mk I involved getting a balance between sensitivity and instability. Since no means of attitude rate sensing was used, attitude control had to



(Smiths Industries)

Figure 11. RAE/Smiths Mk I autopilot (rudder and elevator control): 1930.

be sufficiently sensitive to control long period instability (e.g. the phugoid) without aggravating to an unacceptable degree the short period aircraft instability. The means of achieving the best optimisation was not really understood at the time[44].

The performance of the pneumatic servo was limited by the elastic fluid and by stiction in the servo control valve. Under operational conditions lack of lubrication (the compressed air tended to sweep everything clean), icing, and dirt in the servo valve caused considerable unreliability.

Later these limitations were also found to be severe in the German Askania pneumatic course controller series Lz4 to Lz11 which were used in a wide variety of early Dornier and Heinkel aircraft. Askania abandoned pneumatics[45] in favour of hydraulics for the rudder servo of the Lz14 (Fig. 12) and by 1934 they had adopted, in addition, all electric sensors for their Lz17. The Sperry Co. followed the same route, first abandoning pneumatic servos in favour of electro-hydraulic units.

It is worth mentioning that in the early 1930s electric servomotors were not generally considered to be suitable for automatic flight controls, as the torque/inertia ratio was too low in any device of reasonable weight and size and degree of control. However there were some German systems in the 1930s which used Ward-Leonard coupled electrical drives or continuously running motors from which power could be clutched mechanically into the controls as required[46].

The early 1930s marked the first commercial use of autopilots when Eastern Airlines installed a Sperry A1 in a Condor, one of the last of the commercial airline biplanes. Sperry had their A2 under construction in 1933, this being the main competitor of the Mk 1. The A2 and subsequent A3[47] had some special features and some interesting ergonomic problems (Fig. 13). These were attitude/control displacement systems of the "pilot-assist" category. The functions of the pilot's instruments and of automatic control were combined, which was fundamentally a good economic approach but meant that the gyros could not be precessed to achieve turns as in the Mk 1. Combining the instrument and autopilot sensing also removed the ability to cross-check between the operation of the two.

The significant design point about the A2 and A3 gyropilots however was that they provided in effect a modular selection of sensors and servos which the pilot could employ just as he wished.

The gyropilot could only be engaged from a trim condition and this demanded that instrument output and servo positions were first synchronised or matched. This involved the operation of three knobs. Three further knobs were provided for tuning the servo gains to get the best response after engagement.

Hence the Sperry Co. provided, for application to any aircraft, a system which in effect allowed it to opt out of much of the responsibility for dynamic performance, because this was not fixed, but put into the hands of the pilot by giving him the ability to twiddle knobs.

The A2 and A3 therefore achieved a reputation for high reliability because if they didn't work very well at any time there was a reasonable chance that the fault arose from pilot mistuning, and it was therefore difficult to substantiate a snag in performance.

Engagement of the gyropilot required care and was carried out apprehensively. Slow turns were demanded via the rudder knob and larger turns by operation of the aileron knob. There was no automatic turn compensation in pitch or yaw.

In 1933 the capablities of autopilots were dramatically shown by two record-shattering long distance flights. Between July 15th and July 22nd, Wiley Post flew solo around the world in his Lockheed Vega, the "Winnie Mae", in 7 days, 18 hours and 49 minutes. The Vega was equipped with a Sperry A2 gyropilot after an impressive demonstration of its potential to Wiley Post in the Sperry plant. In the same month, Floyd Bennett, also using an automatic pilot, flew 25 596 miles in roughly the same time.

By the mid 1930s there were many autopilots in general service throughout the world in both civil airliners and military aeroplanes. Most of them employed the principles described, in one combination or another.

A very noteworthy example was the autopilot developed in France by Robert Alkan, on which flight trials were conducted in 1936. It was subsequently put into series production and over 2000 were made. In principle it was similar to the earlier Askania single-axis pneumatic systems and that there was some connection between the two designs is possible. Later versions of the Alkan system used electrically driven instead of air driven gyro wheels, and it was also expanded to give a full three-axis control.

Robert Alkan was a design perfectionist who was responsible for many innovations in the flight controls and navigation field, one being the rotating ball erection system for gyro horizons (the Alkan erection system). This has been used extensively by manufacturers throughout the world, tens of thousands being produced during the Second World War and subsequently, mainly by Bendix in the USA, and SFENA in France for whom Alkan worked after the war. In principle it comprises a disc mounted on the vertical gimbal, which has a circular track on which two ball bearings continuously race, being driven by a rotating vane energised from the spindle of the gyro wheel. The mechanism acts as a vertical pendulum to apply the appropriate erection torques to the gyro wheel. The reliability and simplicity of this device represented a considerable advance over its conventional pendulum or liquid level switch contemporaries.

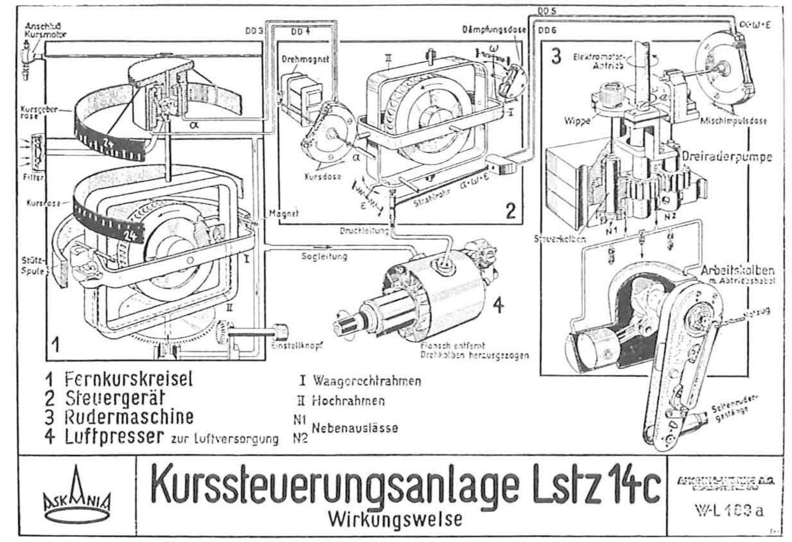


Figure 12. Askania pneumatic course controller Lz14: 1935–1945.

Mention has not yet been made of Siemens LGW in Germany. They became involved in automatic flight controls in 1927 when they were asked by their government to develop and manufacture for a target aircraft, a flight controller originally designed by Johann Boykow, an engineering consultant to the German Navy.

Siemens withdrew from the automatic flight controls business at the end of the last war, but over a period of 15 years they had made outstanding contributions. In 1931, they formed their Air Transport Division and soon after set out to develop a three-axis controller designated the Mk D3 (Fig. 14), under the technical leadership of Dr. E. Fischel[18]. This was an ingenious all-mechanical design employing hydraulic servos, each being actuated directly by a rate gyro appropriately aligned to the axis involved, on the lines of the earlier Askania course controllers. The gyros gave a three-axis angular rate stabilisation and could be precessed respectively to demand turns from a pilot's controller or remote compass, airspeed from a pitot tube, and "wings level" from a pendulum mounted near the cg. The servos were coupled to the controls via torque limiters and a Bowden cable operated disconnect was available in each axis for emergency use. This was, at the time, a very advanced autopilot concept, but only five systems were built, largely because of high cost and internal political factors related to German rearmament.

The German Air Transport Ministry in the early 1930s decided that their prime requirement in the foreseeable future was for single axis automatic course controllers rather than for full three-axis systems. Steady automatic course control was basic to the bomb aiming and release techniques considered at that time. Although they already had available the Askania pneumatic course controllers, they encouraged Siemens to develop a cheap and reliable electrical counterpart. This advice was followed by Siemens with the result that, with both of their major companies concentrating only on course controllers, most of the German aircraft in the Second World War were equipped only with a single-axis automatic pilot which operated the rudder surfaces.

Siemens designated their first course controller design K4 (Kurssteuerung 4). The system weighed about 60 lb and was very similar to the rudder axis of the Mk D3, with the rate-gyro encased with, and directly coupled to, the rudder servo. Engagement was via a fail-safe oil bypass valve. After initial development, a directional gyro control was added to the system to increase the bombing accuracy of the magnetic compass system. This was then designated the K4ü and around 1935 it was delivered to the government test establishment at Rechlin for proving trials, in fact to be conducted by Dr. Möller, who was previously with Askania.

Dr. Möller was charged by Rechlin, at the time, with testing not only the Siemens K4ü, but also autopilot designs from Smiths, Sperry, Constantin and others. The competition which ensued was nicknamed "Olympiade". In the event Rechlin rejected all of the systems in favour of their own development, the Einheits Dreiachsen Steuerung (EDS) which subsequently became known, by virtue of its production source, as the Patin three-axis control.

The K5ü system suffered from the usual problem with early hydraulic servos of sticking control valves and sensitivity of the oil system to dirt. There was also one major problem which was revealed on the Heinkel 219 night fighter. Herr Carl Franke, at the time a test pilot for Heinkel, says "The rudder of this aircraft had a spring loaded tab, and together with the K4ü, there resulted a dangerous oscillation and the whole fuselage end disintegrated. We lost one of our best pilots, Herr Huss. The difficulty could be cured by putting the rate of turn gyro plus actuator housing into a position in the fuselage better related to the nodal point of oscillation". This was probably one of the first examples of what is always now an important design consideration in the siting of rate gyros. Despite the development problems the K4ü was ultimately successful, and in 1936 a contract was placed for 6000 systems.

Further developments led, in the later 1930s, to the Siemens K12[19] which used new small spring-restrained rate gyros separated from the servo units and electrically coupled to them using magnetic amplifiers. As in the earlier models, a magnetically monitored directional gyro was used as the course sensor. (The K12 also formed the basis of the autopilot design for the A4 Rocket, more generally known as the V2.) The K12 was a relatively advanced design. The gyro direction was signalled by a dc pick-off consisting of a pair of hot-wire bolometer elements. A blade carried by the detecting gimbal, cut off one or other of the hot wires from an air jet. The differential change of the bolometer resistances, due to course changes, upset the balance of a bridge circuit which gave rise to the dc output signal. This was combined with the fine wire rate gyro potentiometer output to feed the magnetic amplifier, which in turn drove a moving coil galvanometer to which was attached the hydraulic piston valve. The bolometer was motor driven from the pilot's controller to provide a turn demand capability. The complete system weighed 35–40 lb.

For the V2 (A4) a special high accuracy computer had to be designed which incorporated displacement, rate, acceleration and integral terms, some aspect of this design being necessary to compensate for the inadequate response of the standard Siemens servo actuators being used in this application for which they were not designed.

9. THE SECOND WORLD WAR

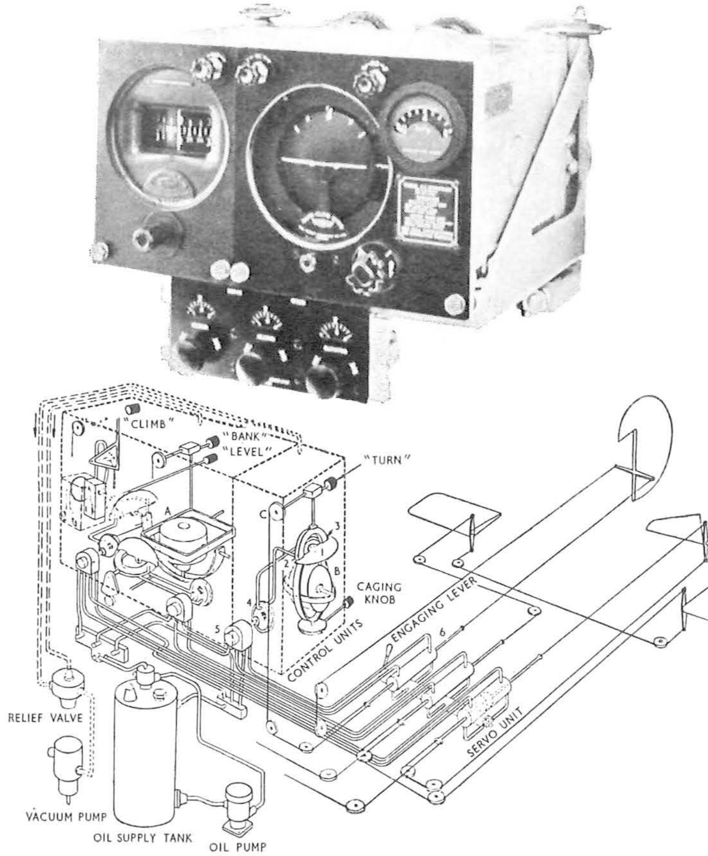
The major British system from the mid 1930s was the RAE Mk IV, developed under the leadership of F. W. Meredith. This autopilot was to become very well known in the Second World War to pilots of Wellingtons, Stirlings, Halifaxes, Sunderlands, Lancasters and others.

The Mk IV[50] was a pneumatic three-axis system, with two twin gimbal gyros, one for rudder and elevator control and the other for aileron control, as in the previous Mk I. The difference was that gyros and servos were in separate packages, following the current US and German trend, but a direct mechanical feedback link was maintained using Bowden cables.

In principle the system was very little different from the Mk I. Unfortunately it proved impossible during the last war to get the production rate of this system above about 800 or 900 sets per month, due to the limit on the availability of precision workers to build gyros and servomotors. This became one of the major bottlenecks for Bomber Command, especially when the long distance raids into Germany commenced, and the need for an automatic pilot, known affectionately to the aircrew as George, was at its peak.

A great deal of effort was therefore devoted to trying to design a system which was simpler to produce but would nevertheless meet the prime requirements of the RAF. Work to this end was put in hand as early as 1940 and the first outcome was the Mk VII[51]. The basic idea was to use a single two gimbal gyro only to give a combined roll/yaw control via ailerons, to leave the rudder free with no automatic control, and to drive the elevator from airspeed error and error rate.

This new system halved the requirement for gyroscopes and had two instead of three servometers. It therefore promised to give a considerable production saving compared with the Mk IV, and was pursued for this reason only. The first trials proved satisfactory, but in time another important lesson in automatic control history was learned. This was that barometric rate information, especially airspeed rate, is not a good control term in gusty conditions. The RAE tried hard to get this system to work, but the control of the elevator from airspeed terms was



(Sperry (U.K.) Ltd)

Figure 13. Sperry A3 gyropilot: *circa* 1936.

eventually abandoned. Instead a further output was taken from the inner gimbal of the single roll/yaw gyro, and used for elevator pitch control. This gyro arrangement was also merely an expediency, as it was really satisfactory only in level flight. Turns had to be done either manually, with the autopilot disengaged, or automatically by manipulating the the pilot's pitch controller to keep the nose up. Despite this unsatisfactory operating feature, brought about by the economical single gyro concept, the system was accepted by the RAF and was designated the Mk VIII. It subsequently became the basic installation in the later variants of the Lancaster and Lincoln.

The system was also coupled to a magnetic compass to give automatic course keeping, as had been a feature of the German course controllers from the mid 1930s. The

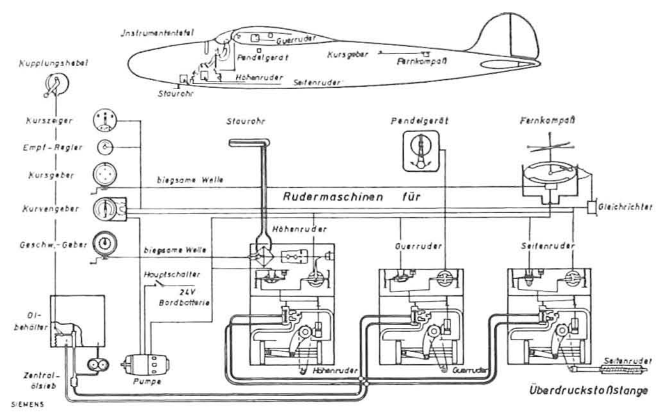


Figure 14. Siemens D3 three-axis autopilot: *circa* 1932.

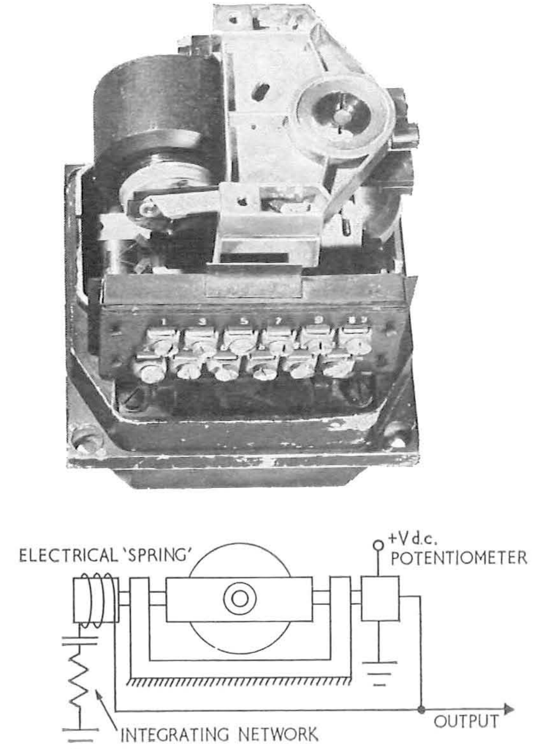


Figure 15. Siemens K23 electrical 'spring' rate gyro.

Mk VIII, as inferred before, would not perform automatic turns onto a magnetic heading, but could be locked onto any heading achieved manually. The directional monitoring of the gyro by the magnetic remote reading compass was effected by impinging an air jet on the appropriate gimbal to precess the gyro. The whole system was barely stable, and in fact the "jinking" evasive action could be programmed automatically by making the system deliberately unstable, giving a $\pm$ 15° amplitude roll with a 30 second period. It is said that the RAE flight test engineers who developed this aspect of the Mk VIII found a use for its bowl-shaped lid which was not related to keeping dust out of the precious gyro. This automatic jinking system was not used finally in service.

In 1943, production levels of the Mk VIII system increased to 50% above the Mk IV, thus justifying the adoption of a less sophisticated technical solution.

One of the major problems of the Mk IV and the Mk VIII as used in the Second World War was lack of synchronisation of autopilot demands and flying controls prior to engagement. This was most serious in pitch, as the datum position of the control column varied considerably depending upon the aircraft loading, fuel usage, and crew movements. It was nearly impossible to ensure smooth engagement and an order from the cockpit "standby to engage autopilot" was an invitation to tighten straps. Later modification were included to eliminate this engagement problem by giving a synchronising action as was current in the US autopilots. Other minor changes evolved the Mk VIIIA which was installed after 1946 in the BOAC Lancastrian, Halton, Solent and York aircraft.

During late 1945 a number of accidents to British aircraft were traced to dirt and swarf in the pneumatic servo valves. To deal with this the control of manufacturing quality was improved, as was also the on-board filter system. In addition override spring "bonkers" were installed. These were negative feedback levers between the output rams and input valves which incorporated dead-space so that they were normally ineffective. However if a valve at any time stuck in a hardover position it would be freed by the reverse action of the "bonker". From this time increasing attention was paid to the safety problems in the design of high authority servo controls and engage mechanisms.

In addition to those already mentioned, a number of American autopilots came into wide use later in the war. These were primarily the C-1, from the Minneapolis-Honeywell Regulator Co., the General Electric Co. (USA) Mk IV and the Sperry A5. All were fairly advanced designs.

The Minneapolis-Honeywell C-1 was an all-electrical system which served as an all-purpose autopilot and worked also with the Norden Stabilised Bombing Approach Equipment. Its main new feature was "erection cut-out" and a single knob turn controller. It also had attitude and heading hold modes, and used constant speed motors with electrical clutches as its servo concept. The C-1 was a basic installation in the Flying Fortress (B-17), Liberator (B-24) and Super Fortress (B-29).

The General Electric autopilot was simpler, combining instrument information for pilot and autopilot and used electrohydraulic servos. All of the American systems were basically attitude/displacement autopilots.

The Sperry A5 was an extremely accurate electrical autopilot using electronically generated first and second derivatives of attitude signals to obtain the very quick response needed when coupled to the Sperry bombsight. The servomotors were hydraulic using the new concept of force-feedback and had, like the older Askania Lz14 and Lz17 rudder servos, a self-contained electric motor/pump and reservoir. The A5 system was well ahead of its time in this respect and would now be described as "power-by-wire". However, it weighed 250 lb and was bulky and complicated. As fitted to the Flying Fortress and Liberator, the maintenance of the flying control systems required to keep the system operational proved to be such a burden that installation of it was avoided whenever possible in favour of the more basic Minneapolis-Honeywell C-1.

A later Sperry system, the A12, was similar to the A5, but employed electric instead of electro-hydraulic servomotors. This was used on later production models of the Liberator and after the war gave excellent service in civil aircraft.

One outstanding automatic flight controls development of note was that made in Germany for fighter aircraft. The Luftwaffe required a simple cheap lightweight course controller suitable for fighter aircraft in good and poor visibility and which could be produced in large quantities. One of the main reasons for the requirement was to cut down the high losses sustained in delivering aircraft to the front. Wartime ferry pilots are often bad navigators. There was a desire to minimise or to avoid the use of devices such as free gyros, with their attendant precision production problems, just as there was in England, when the Mk VIII was evolved from the Mk IV.

Siemens set out to design such a system as early as 1939 and finally produced a series of controllers of which the most successful was the K23. The key to this design was to employ an integrating yaw rate gyro (Fig. 15), using an electrical spring restraint energised from a gimbal position potentiometer via a capacitor. The potentiometer voltage is proportional to "rate of turn" plus "bearing deviation". This demanded a rate of movement of the rudder control surface via a shaping network, magnetic amplifier and a dc electrical servo, controlled by a polarised relay. Servo feedback was economically derived from measurement of motor armature voltage and current. The device also included a pendulum feedback "to offset increased gain" in a steady bank condition. The "integration constant" or monitor for the integrating rate gyro was provided by remote reading magnetic compass, and turns could be made by applying a voltage to the rate gyro torque coil. This was one of the most simple and elegant automatic flight control systems produced up to the end of the Second World War, and in some respects anticipated the "rate-rate" control subsequently widely employed by Smiths in England.

Another very sophisticated automatic control system referred to previously was the EDS developed for the Luftwaffe at Rechlin between 1933 and 1939 by Dr. Möller. This was a three-axis rate-rate system. The dc signals from the various measuring units were compounded in multicoil galvanometers and then amplified by Ward-Leonard coupled generators which drove the servomoters. The rate gyros were of a special design involving multiple restrained gimbals so that the output signal was a function of angular acceleration as well as angular velocity. The system also included a vertical gyro to measure bank angle and a directional gyro to measure heading. Airspeed and the first derivative of airspeed were also used.

The system aimed to emulate the type of control effected by a human pilot, having been designed as a result of extensive analysis of recordings of repetitive mountain route flying by test pilots. It was claimed by its designer Dr. Möller, to be "elastic and soft" with regard to stabilisation and suppression of oscillations, but precise and free of residual "hang-off" as regards control of heading.

This system was personally "accepted" by General-luftzeugmeister Udet and subsequently manufactured from 1941 by Patin, although elements for it came from a wide range of subcontractors. The main contribution of the Patin company to this development, incidentally, was the invention and production of very fine wire potentiometers and special actuator relays.

A single-axis version of the Möller/Patin three-axis controller (then designated PDS) was designed for fighter aircraft. Known as the PKS-II, it was an alternative to the Siemens K23 and was also produced in very large numbers.

Another difficulty arising out of the development of small fighter aircraft, first in the Henschel Hs129, led to the development of "short period" stabilisers, or "yaw dampers". Artificial damping was contemplated on the Hs129 because of the extremely small rudder/fin area, its high yaw inertia due to armour plating, and the awkward design of the cockpit and its controls. In fact during the war there arose a general requirement for additional damping of the lateral motion as a consequence of aero-dynamically cleaner aircraft designs.

The Hs129 yaw damper was developed by Dr. Karl Doetsch[52] over the period 1942–1944 at Berlin-Aldershof. Later "due to the bombing" he was transferred to Travemünde near Lübeck, where the Fighter Development Station was formed, and here he finished the work around January 1945, on what became the world's first series coupled yaw damper.

Doetsch first thought of the idea after observing the effect of a misuse of the simple rudder course controllers. If a heading change of more than 30° was dialled into these systems the demand limited and the system became just an angular rate control, giving a damping effect about the yaw axis. He first tested the concept himself in an Fw190 and later in an Me262 (the world's first operational jet fighter). On the Fw 190 he tried to implement the action by pneumatic operation of the rudder pedals but soon appreciated that "the solution had to be quite different from customary automatic control, because the latter did not permit the pilot to continue manoeuvring the aircraft through the primary control (stick, pedals). The problem to be solved was how the human operator and part automatics could live together". Dr. Doetsch says further "on the Hs129 I solved this problem by letting the autostabiliser apply aerodynamic moments only to the rudder by means of a small servo tab in superposition to, and practically without interference with the pilot's efforts on the pedals. Also, of course, the autostabiliser signal had in all these cases to be transientised in order to eliminate sustained control opposition during a turning manoeuvre".

The Hs129 damper device (Fig. 16) used a spring restrained gyroscope operating, via a series of contacts, a two position rotary magnet as a servomotor. This was just powerful enough to operate directly a rudder tab through a $\pm$ 2° deflection in a bang-bang fashion. There was a 7 cps standing oscillation and for an intended turn a contact on the joystick started a small motor with a delayed-action clutch which slowly turned the contact assembly to "washout" any steady opposition by the damper action. The unit was housed in the vertical fin of the aircraft—its logical home.

At the close of hostilities, when the German engineering teams were dispersed, "a team of young British scientists" met up with Doetsch at the tiny village of Trauchgau (near Oberammergau). The outcome was that Dr. Doetsch joined the RAE at Farnborough and remained in England until around 1960. Here he continued his work on yaw dampers, among other aspects of automatic flight controls, and devised a system for "the Gloster Meteor and subsequently other fighter aircraft which used continuous tab control through limited authority tab deflections. Thereby the difficulty of mixing the pilot's control inputs on the rudder pedal and the autostabiliser inputs without mutual interference was solved in an elegant way".

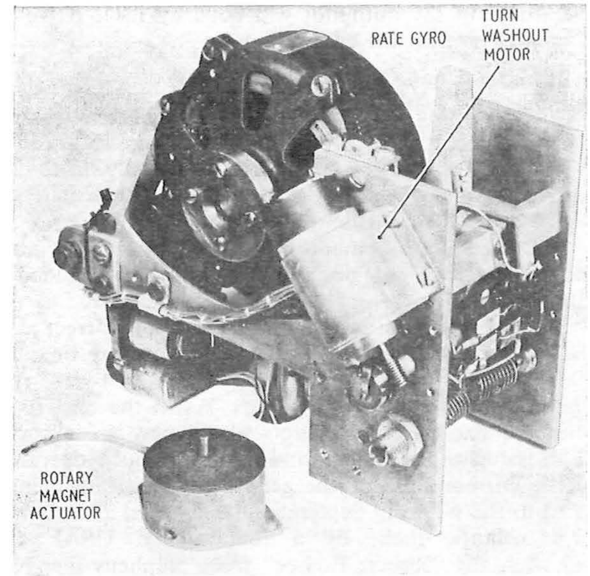
Later the advent of the hydraulic power control and artificial feel made the implementation even simpler, as both damper and pilot inputs could be added and applied to the same control surface.

10. POST-WAR

The removal of the pressure of hostilities at the end of the Second World War gave industry, and the various technical establishments of the allies, a chance to review what had been achieved by that time in the automatic flight controls field. Many German engineers also moved to the UK, USA and the Soviet Union where they contributed a great deal to the immediate post-war thinking.

One such technical review was carried out at the Royal Aircraft Establishment in England which was to have considerable influence on the future automatic flight controls activity in this country.

Until 1939 designs of automatic controls equipment had been developed largely by empirical innovation (creative synthesis). In most cases they were then analysed and refined by whatever methods were available at the time. The available technology determined to a large extent what sensor and control devices were used, as is always the case, but it was normally from the results of flight testing that specific analysis and optimisation were generated. By today's standards, the supporting analytical work which was done was limited, even though the theory and associated analytical methods of Bryan, Bairstow, Melvill Jones and Thompson, Garner[53], G. Doetsch[54] and others were available and understood by the practical designers, certainly in Europe. The difficulty was that the combination of the aircraft stability and automatic control equations was so complicated that it was very laborious



(Royal Aircraft Establishment)
Figure 16. Yaw damper for Hs 129: 1942–44.

and time-consuming to evaluate any solutions. To solve the uncontrolled aircraft equations alone involves at least the factoring of quartics, and the addition of auto-control feedback increases these up to several higher orders. It was cheaper and quicker to get results empirically. The situation was made worse by the difficulty in dealing mathematically with the non-linearities in the available devices from which complete systems were constructed. Even after the Second World War more than five years passed before electronic analogue computers became readily available to assist with the analysis and optimisation of automatic flight controls designs. Gradually it became realistic and economic to use these rather than flight test hack aircraft which subsequently declined in popularity.

The first post-war civil and military aeroplanes were fitted with equipments which were limited developments of wartime devices. However electrical transducers, electronic (valve) amplifiers and electric servo systems became widely employed and pneumatic systems became obsolete. RAE in an early post-war report[55] had said "Among the many difficulties associated with the use of compressed air, probably the most serious limiting factor is the inflexibility of the system for linking to external sources such as radio beams . . . The basic information obtained from such external sources is invariably in the form of electrical quantities and the problem of obtaining corresponding air pressures involves considerable complication and inelegance. With an electrical autopilot the external signals can be coupled directly. An additional advantage of the electrical system is that it enables the servomotors to be installed relatively close to the control surfaces they operate, and remote from the main gyro units, since electrical and not mechanical connections are required between the two items. This is particularly important in large aircraft, since the performance of the autopilot is (then) less sensitive to variations in the main control circuit (e.g. lost motion or slackness)."

The need for an "all electric autopilot" had in fact been obvious for some considerable time. As was said earlier, Germany had produced experimental versions, and in the United States systems by Sperry, Minneapolis Honeywell and others had been in service during the war.

In 1938–39 F. W. Meredith, at Smiths, had designed and tested an all-electric fully manoeuvrable autopilot using free-gyros and a manoeuvring platform. However this was never put into production because of the outbreak of the war, when all effort in Britain was concentrated on existing hardware.

The desire for automatic radio coupling, which was to lead ultimately to automatic ILS approaches and automatic landing by transport aircraft, became sufficiently strong for experimental work to be conducted in the early months of 1944 just before the end of the war in Europe. The Telecommunication Flying Unit at Defford, Worcestershire, tested an American SCS (Signal Corps System) 51, the airborne portion of which was fitted into a Consolidated Liberator (B-24) to demonstrate radio approach capability to the Eighth American Air Force. The Americans flying in Europe at this time had become very upset about the English weather and were most interested in low visibility approach aids.

The equipment was brought to England from the USA by a team led by Major (later Lieutenant-Colonel) Francis Moseley, formerly a development engineer in the Collins Radio Co.[56]

At Defford the responsibility for demonstrating the system was given to Group Captain J. A. McDonald[57], then in command of TFU, and a flying team led by Wing Commander F. C. Griffiths.

The radio guidance was very successfully demonstrated in the Liberator, using a pilot's cross-pointer "zero-reader" instrument, and its success prompted Frances Moseley to produce a "breadboard" (first put together in the basement of his home) to couple the SCS 51 to the autopilot. This was first tested in October 1944 in the Liberator, which had a Minneapolis-Honeywell C-1 autopilot, and later the "Moseley Box" and its associated equipment was transferred into a refurbished Boeing 247D, (one of the world's first all-metal monoplanes) originally built in 1931 for United Airlines. This had the desirable features that it could fly as slow as 50 mph and approach to land at a glide angle as low as $2\frac{1}{2}$°.

The first fully automatic approach and landing was demonstrated to the Auto-Approach Panel of the Ministry of Aircraft Production by Wing Commander Griffiths and Squadron Leader J. Stewart on 16th January, 1945. This was in daylight—but five days later, an automatic landing was done at night, during the "blackout".

The Boeing 247D completed about 300 hours on automatic approach and landing trials. The Defford testing also involved the use of a Rebecca-Eureka DME equipment for auto-navigation and to enable the pilot to read the "distance to go" during the approach to land.

The system was also tried on the British Lancaster and Halifax aircraft but their angle of glide was too steep and also being tail-wheel aircraft the achievement of good repetitive three-point landings proved too much for the automatic control system. The conclusion of this Defford activity was to recommend that such systems should be used only for nose-wheel aircraft. This was very unpopular at the time in view of the number of tail-wheel civil transports which were on the drawing boards.

The Defford activity had in fact been an extension of the TFU radio work into the province of automatic controls. The RAE thought perhaps that automatic landing should be tackled the other way round. In the event some of the Defford team, with their equipment, were transferred later to Martlesham Heath to join up with staff from Farnborough as part of the action involved in setting up the RAE Blind Landing Experimental Unit, which continued the pioneering work on automatic landing.

11. THE POST-WAR AUTOPILOT

From the end of the Second World War the general concepts of automatic flight controls throughout the world converged onto a common approach to the problems involved both from an understanding of what was required and also because there was a more rational appreciation of what was achievable from practical technology. The various ideas, inventions and experiences of the past solidified into a universally accepted whole.

In an RAE monograph (No. 2.5.03) published in August 1947, H. R. Hopkin and R. W. Dunn gave a classical summary of the aircraft stability and autopilot technology up to that time. The definition of a basic autopilot remains a good one even to the present day. There is no better way to continue than to quote it direct: "Most autopilots are employed for flying the aeroplane under conditions of moderate bank angles (say not greater than 45°) and small angles of climb or dive (say within 5° up and 10° down) . . . It is interesting to examine the basic control laws that have been used . . . the majority of autopilots have applied control in response to angular disturbance in roll (ϕ), pitch (θ) and yaw (ψ): in some cases time derivatives or integrals of these angles are added. The only variations occur in elevator control, where functions of the speed error (u) or the height error (h) have been used. Thus the basic control law of most autopilots is given by

$$\xi = F\phi$$
$$\eta = G\theta$$
$$\zeta = H\psi$$

where ξ, η, ζ, are angular displacements of the ailerons, elevator and rudder respectively, from equilibrium positions: and F, G and H are constants known as gearings.

"It should be noted that a number of autopilots . . . attempt to establish these equations by producing (say) aileron velocity $\dot{\xi}$ proportional to rolling velocity $\dot{\phi}$, i.e. $\dot{\xi} = F\dot{\phi}$ instead of $\xi = F\phi$. These autopilots are said to use a rate-rate system as opposed to the more conventional displacement system. At this stage we do not discriminate between these types since we are concerned with basic control laws: there are of course differences when control engine lags, etc, are allowed for.

"The addition of angular velocity and acceleration terms on the RHS of the basic control laws must improve the stabilisation of the aeroplane because the autopilot is receiving valuable extra information about the aeroplane's motion. Fundamentally the aeroplane is disturbed by moments, which instantaneously produce angular accelerations, so that an autopilot required to restrict angular deviations should logically apply correcting moments as soon as any angular accelerations appear. In other words we should expect control equations of the form $\xi = F\ddot{\phi}$. Such an autopilot however would not heed a steady angular velocity, and a velocity term would need to be added to the equation to remedy this. It would appear that the further addition of a position term would prevent the aeroplane from acquiring a steady angular error. However it is possible for the equilibrium position of the control surface to change subsequent to the time when the autopilot was first engaged. Thus disturbing moments may be built up due to changes in cg position caused by consumption of petrol, movement of passengers, etc. Such non-transitory moments must be balanced by a permanent deviation of the control surface from its original position. With (say) an equation $\xi = F_1\ddot{\phi} + F_2\dot{\phi} + F_3\phi$ we can obtain a steady aileron deflection ξ_T and no rolling motion ($\ddot{\phi} = \dot{\phi} = 0$), only by having a steady bank error $\phi = \xi_T / F_3$. Errors of this kind (usually a few degrees) may be trimmed out by human intervention, but the autopilot will cope by itself if we add an integral term to the equation, e.g.

$$\xi = F_1\ddot{\phi} + F_2\dot{\phi} + F_3\phi + F_4\textstyle\int\phi . dt$$

"The trimming term must be the time integral of some variable which is zero in the desired steady state . . . It sometimes happens that monitors, essentially introduced to restrict errors of gyroscopic instruments, incidentally add integral terms of the trimming type.

"Historical development has not followed the above logical sequence, and no autopilot has yet included all four terms . . ."

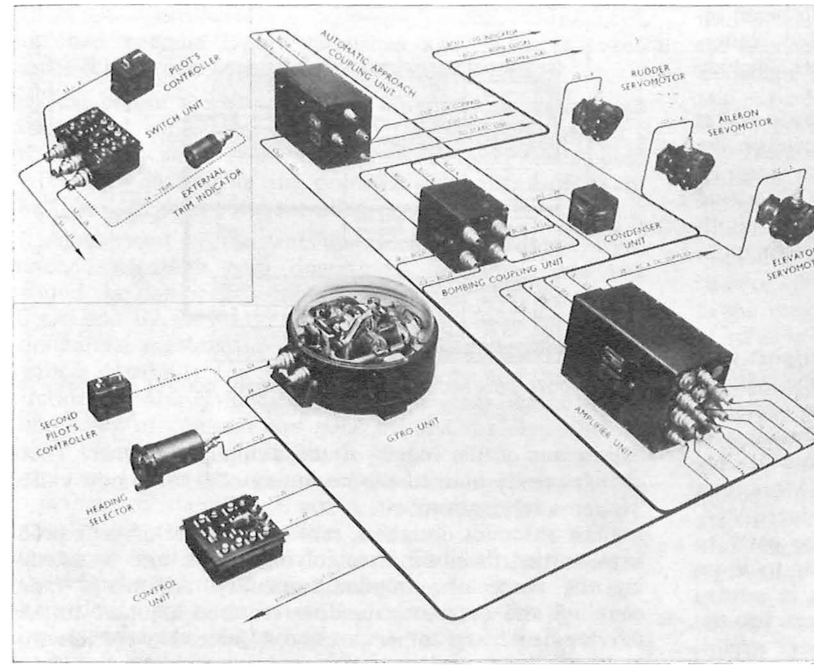
This last statement by Hopkin and Dunn, correct at the time, was soon to be reversed. It was at this time that civil airlines were contemplating new post-war route structures with very long-haul legs. As in the past it was considered that automatic pilots would play an important role in reducing the fatigue and tedium of such operations and the current state of the art was dramatically demonstrated to the world in September 1947 by an all-automatic North Atlantic flight by a four-engined USAF C-54 Skymaster, the "Robert E. Lee" from Stephensville, Newfoundland to Brize Norton in England[58].

The flight was completely automatic from take-off to touchdown. The aircraft was fitted with a Sperry A12 autopilot and a Bendix automatic throttle. It was arranged for the various modes of operation and radio selections to be programmed automatically from a store comprising a series of punched cards in a computer. The aircraft thus proceeded over the Atlantic by homing onto and overflying weather ship radio beacons one after the other. The landing at Brize Norton involved no special automatic device. The aircraft literally flew down the ILS beam in its final low weight condition until it contacted the ground.

The whole operation was hailed by the *New York Times* as "a triumph of automatic control," which fulfilled one aim of the instigators of the demonstration who were looking for a favourable US Government financial vote to continue their research work. The elements of the system were in fact relatively simple.

The pressures at the time from both military and civil quarters for new sophisticated autopilots must have been great, for in Britain alone at the end of the war, no less than three parallel developments of electric autopilots were commenced. Government contracts were placed with Smiths for the "Type D", later to become the military Mk 9 and with Sperry (UK) for the "Type E", later to be the Mk 12. The third development was carried out at the RAE, using ex-German sensors and servos. In the event the RAE system was developed into a series of autopilots used in drone target aircraft such as the Jindivik and Meteor. The Smith Mk 9 (Fig. 17) military autopilot spawned a corresponding civil version designated the SEP 1.

These were to be Britain's first all-electric autopilots.[59] Smiths adopted the so called "rate-rate" concept for their systems. This was to be developed under F. W. Meredith, who moved to Smiths from the RAE in 1938. The rate-rate control meant the abandonment of the more conventional displacement system whereby the amount of surface angle applied is proportional to the amount of aircraft deviation from datum. In the simplest mathematical terms there is no difference between the two concepts but, in practice, the rate-rate system, which employed platform mounted rate gyros instead of free gyros, offered advantages of robustness, freedom from gyro gimballing errors, and most important, intrinsic engagement synchronisation. Because the rate-rate system involved rate-demand rather than position demand it was less likely to apply sudden movements to the surfaces. This was an important factor



(Smiths Industries)

Figure 17. Smiths Mk 9 autopilot.

in the decision to select this form of control, and was much influenced by the rising sensitivity of operators and certification authorities in the late 1940s to the dangers inherent in the use of high authority automatic flight controls.

The Mk 9/SEP 1 autopilot was a three-axis one using ac inductive pick-offs and ac servomotors of the hysteresis type, which were especially developed for this system. Each axis employed a monitoring device (pendulum for pitch and roll, and compass for yaw) for correcting any slow datum drifts. Turns were demanded by appropriately motoring the gyro platforms with respect to the airframe. The short period datum position of the gyro sensor could be disturbed by large gusts causing servo velocity saturation, but the hysteresis motor was designed to minimise this effect and the long period pendulum or compass monitor soon re-established the datum.

The amplifiers of the Mk 9/SEP 1 were a combination of vacuum tube devices, for handling low level signals, and magnetic amplifiers for the servo drives. The vacuum tubes were individually tested and preconditioned before installation but they constituted a major reliability problem.

In a paper to the Royal Aeronautical Society in 1949 F. W. Meredith said: "It is unfortunate that our manufacturers of valves (vacuum tubes) cannot see their way to producing special valves for electronic equipment requiring a high order of reliability. There is a large field in industry for electronic control if the required standard of reliability could be guaranteed. The American valve manufacturers have seen this and are producing special valves for the purpose. Unless something is done about it soon, either the job will be done without valves or the art of electronic control will be in danger of becoming an American monopoly". Something was done; a series of "ruggedised" valves was produced, and many of them were American.

In the United States by 1947 many of the new aircraft on the drawing boards had a greatly expanded speed and altitude range, and exhibited the type of characteristics which Karl Doetsch wrestled with towards the end of the Second World War. The necessity for "dutch roll" damping had also spread to the larger aircraft, and a considerable amount of work was carried out, notably by the Boeing Airplane Co. to improve artificially the lateral stability of the XB-47, a four jet bomber being developed for the US Air Force. They chose the same solution previously adopted by Doetsch, a "yaw damper consisting of a yaw rate gyro pick-up that operates the rudder to improve the airplane damping in yaw". The XB-47 had irreversible power operated controls and pilot artificial "feel".

The XB-47 yaw damper was a series actuated device of limited authority. Hence it did not reflect its demands onto the pilot's pedals and conversely, it could be "overpowered" if necessary. This system was probably the first series yaw damper operating into hydraulic power controls. Its design and performance was extensively described in 1950 in a classical paper by Roland J. White[60]. Extensive work was also done on stability augmentation at this time by Northrop on the flying wing designs (B-35 propeller version and B-49 jet). Soon short-period damping was commonly applied to all three axes, roll and pitch being added mainly to counteract the destabilising effects of control system lags and hence allow the use of higher attitude gearings which would give better autopilot accuracy. The design of the three-axis short-period stabilisers then became much more sophisticated in order to achieve standard criteria which were defined for handling, mainly for combat aircraft types but also later for civil transports. Much of the responsibility for the short period stability of an uncontrolled aircraft thus became transferred into the area of automatic controls, and electronic artificial stability of the aircraft (i.e. about body axes) became widely used. This was the advent of the "inner-loop" control system, as distinct from the previous traditional automatic pilot controls, which were referenced to earth axes.

It can be imagined that such dependence, as in earlier days, was not always welcomed by designers or pilots. A young British engineer, when working on the stability problems of a famous French supersonic jet in the mid 1950s, was told by an equally famous test pilot, "she flies, but she shakes my backside"—a liberal translation. A very elaborate manoeuvre command stabiliser was subsequently fitted in the production machine.

Several generations of aircraft have now employed such systems, ranging from simple control loops employing only rate gyros with fixed gain amplifiers and servos, through to systems such as that supplied by Honeywell for the North American X-15 experimental rocket aircraft, which used a complex array of angular, angular rate, acceleration, manometric and pilot's control stick sensors, and a computing system which could adjust the performance capability of the aircraft according to the outcome of its own response. That is, it was "self-adaptive". The current generation of high performance combat and transport aircraft all employ some form of stability augmentation.

The practical outcome of the expansion of the use of automatic controls in modern aircraft is that one set of sensors, usually comprising rate gyroscopes and/or accelerometers, referenced to aircraft axes are allocated the task of coping with the short period or so-called "inner-loop" stabilisation task (sometimes called "stability augmentation") while vertical and directional gyroscopes, inertial platforms, manometric sensors (e.g. height and speed) and various guidance devices such as radio beam receivers and other sensors deal with the so called "outer-loop" control requirements, which, for example, include stabilisation of the phugoid in the pitch case.

Of course the complexity of present day aircraft makes this summary of the problem look simple; however the basic principles remain valid. In block diagram form, a modern automatic flight control system (AFCS) would incorporate "inner loop", "outer loop", logic and pilot's controller aspects (Fig. 18) and would have a large number of potential modes of operation.

12. THE 1950s

In Britain the Smiths Mk 9 and SEP 1 transport and bomber aircraft autopilots were followed by the Mk 10 military system and corresponding SEP 2 civil version, both having radio coupling. These were substantial and highly successful developments which had a considerable impact on British automatic controls capability. (More than 1000 civil SEP 2 systems were subsequently produced.)

Both of these systems were in service by the early to mid 1950s. The principles employed were similar to those of their predecessor's, but advantage was taken of advancing technology to substitute magnetic amplifiers for the vacuum tube amplifiers of earlier types. This gave a considerable improvement in reliability. The new system also included an automatic pitch trim system. This had been available but was not favoured in the earlier systems for safety of runaway reasons. The control modes of the early SEP 2s were attitude stabilisation, altitude and airspeed locks, automatic radio coupling to ILS localiser, glide path and VOR (VHF Omni-Range). It would also turn the aircraft to lock it on to any pre-selected heading. The weight was 80 to 110 lb depending on the optional facilities incorporated.

The SEP 2 and its United States contemporaries such as the Sperry A12 and the Bendix PB10 (which included autothrottle control of airspeed on the approach) gave to pilots, for the first time, a smooth continuous operating capability which would allow more than 90% of a civil transport flight to be conducted under automatic control. Indeed, with adequate experience on the transport aircraft of the 1950s some airlines were able to have the autopilot engaged down to "break off" heights of only 300 to 200 feet above the airfield, which was not to be improved upon for more than a decade.

Also in the early 1950s, especially in the military field, further significant decisions had been made affecting automatic control designs. First the gyro reference problem was tackled. In the past the gyros associated with the automatic flight controls had suffered from cross-coupling and gimballing problems which restricted the manoeuvres which could be performed under automatic control. For highly manoeuvrable aircraft it was now decided to produce special gyro platforms to give the aircraft vertical and azimuth references independent of the manoeuvres performed. These references would be available to the autopilot as well as to other systems. In general they took the form of twin gyro platforms with multiple servoed outputs and sufficient gimbals to ensure that they would be free from gimballing errors or toppling dangers. They would therefore at all times, with fairly high accuracy, give true Euler angle readouts of bank angle, pitch angle and yaw angle. Thus free-gyro problems were removed from the province of the autopilot designer.

A similar decision was made with regard to manometric measurements. These were required in the aircraft for a number of purposes apart from their use in the autopilot. The concept of the central air data computer was then established. This also took the problems of air data deri-

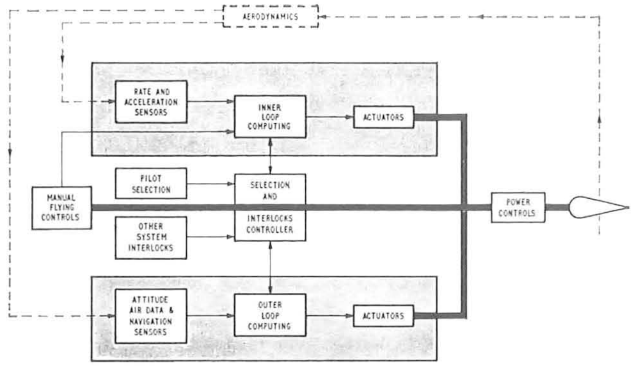


Figure 18. Modern automatic flight control system (block diagram).

vation out of the hands of the autopilot designer. These changes really marked the beginning of what is now called "systems integration".

The autopilot designers, relieved of some of their problems, turned their minds to solving others, and to extending the scope of autopilot capability. Automatic radio coupling and automatic landing required a lot of further development, and other areas of interest were electro-hydraulic integrated actuation and power control systems, and advanced stability-augmentation systems for high performance jets.

The requirements and the technology available then came together to usher in the present era when whole systems are designed specifically to suit the aircraft in which they are fitted. This was a new approach to the design of automatic flight controls systems. The new aircraft were designed for special roles and the automatic controls had to follow suit.

Indeed from the early 1950s, there ensued such a proliferation of automatic control designs, and such a multitude of aircraft types, each with its own special characteristics in relation to automatic flight controls, that it is no longer possible here to cover all of the separate systems individually. For example, if it is appreciated that the Bendix Co. alone, as one of about six major world suppliers, has provided automatic flight control systems for more than 70 aircraft types since the Second World War, the magnitude of the total world activity will be appreciated.

There have however been a number of significant milestones in the development of the technology of automatic flight controls which apply to all of the vast number of separate designs which have come to fruition over the past 20 years or so. It is therefore appropriate to assess this more recent history from a general viewpoint, although in some cases it is still relevant to illustrate the key milestones by mentioning particular designs. Where examples are used these have been chosen from information most readily available, the choice not in any way being meant to reflect particular advantages or otherwise. Dr. Walter Tye has described this problem rather well in a different context: "a tree in the heart of a wood must be forgiven if it knows best the trees in its immediate vicinity and if its perspective of the whole wood is restricted".

From this point an attempt is also made to consolidate both background and foreground so as to get the early work and the more recent explosion of technology into perspective.

13. ANALOGUE SIMULATION

By the end of the Second World War, as has already been said, the computation of the stability conditions of controlled aircraft, including the characteristics of the

automatic controllers (i.e. lags, deadspaces, compliances, etc) had become highly laborious and in most cases, impossible to carry out.

Just before the war, the German rocket scientists had constructed an electromechanical "differential analyser", which was to some extent programmable, and hence could be used to investigate the potential dynamic stability of their tail-launched autocontrolled designs.

At the end of the war the electronic analogue computer, using high gain operational amplifiers was just around the corner. By the late 1940s they were being put to use and by the early 1950s there was a whole range of commercial machines available. This therefore opened up again a capability for analysis of stability and control of aircraft previously denied to the designer because the complexity of controls had gone beyond the capability of paper calculations. With 20 to 40 low drift operational amplifiers it was possible to simulate the incremental performance and stability of, say, a supersonic fighter in real, extended or compressed time, with an accuracy mainly dependent on the aerodynamic information used, and the ease of adjustment of the computer parameters allowed much design investigation to be conducted. By this time also experimental flight and wind tunnel data and the analytical methods related to the construction of aerodynamic derivatives for the new types of aircraft had been extensively developed; so overall, the modelling of flight control systems and their preflight optimisation became an everyday activity. In addition, the analytical and experimental methods for the design of automatic control systems were fairly well developed. The history from Routh (1877) to Nyquist, Bode and Evans was splendidly summarised by Bollay in the Fourteenth Wright Brothers Lecture to the Institute of Aeronautical Sciences in December 1950[61]. The graphical techniques developed by this time could be easily used by practical designers on an everyday basis so that analytical calculations and rig work could be performed to determine, in advance of an aircraft's first flight, what might be the effects of all aspects of automatic flight control designs.

All of this could now contribute to a bank of knowledge gained during early design of an aircraft, and add a high degree of refinement to the design prior to its first flight, and hence much expensive modification could be avoided.

In some cases simulated flight tests were conducted on the aircraft itself, with aerodynamic loops closed through mobile analogue computers (Fig. 19). In general the results obtained gave a fair correlation with subsequent flight tests and it therefore became possible to reduce further the amount of the more expensive flight testing by "filling in the gaps and corners of the flight envelope" and the associated failure effects by tests on the ground simulation rig. This established the validity of the "Iron Bird" technique which later was to become a normal design procedure in aircraft controls development.

14. THE SOLID STATE ERA

By the early 1950s all automatic flight control systems were designed to reduce to the absolute minimum the number of moving parts in the more complex computers which were then being demanded. Suitable transistors were not readily available until the mid-1950s, and valves (electronic tubes) were most undesirable, so for a short period the magnetic amplifier came again into prominence. These had been used extensively during the Second World War by the German automatic controls designers, but they did not at the time find favour elsewhere and most of the autopilots of the immediate post-war period used valves. The magnetic amplifiers of the early 1950s were considerably improved over their wartime counterparts because of the development of higher permeability magnetic materials and the availability of the new germanium and silicon diodes. They gave a very significant increase in reliability to the "black box" elements of automatic flight control systems, but their use in new designs was restricted to the very few years before the advent of a wide selection of reliable transistors.

It is interesting that a large proportion of the transport and combat aircraft in service in the world today were designed during this brief period and hence have autostabilisers and autopilots which still employ magnetic amplifiers. In many cases, these were only applied for servo power amplification, as the necessary high power transistors which ultimately replaced them did not become available until much later than the low power ones. However many of the computers designed in the early 1950s also used magnetic amplifiers for basic analogue computation.

The Elliott Mk 13 and subsequent automatic flight control systems installed in the English Electric Lightning are representative of such technology. These have magnetic "operational amplifiers" in which the majority of gearing adjustments in the computers are effected in the amplifier feedback loops. These also employed the newly available silicon diodes and ultimately the Lightning system was designed so as to be able to withstand a temperature environment limited only by the dissipation capability of the silicon junctions (Fig. 20).

15. HIGH PRESSURE HYDRAULIC SYSTEMS

Another special feature of combat aircraft from the early 1950s was the use of high pressure (3000 psi) electro-hydraulic actuators and power controls, made necessary because of the higher response rates and lower weights required to match the exacting control demands of high speed jet aircraft. Most autostabiliser actuators were of

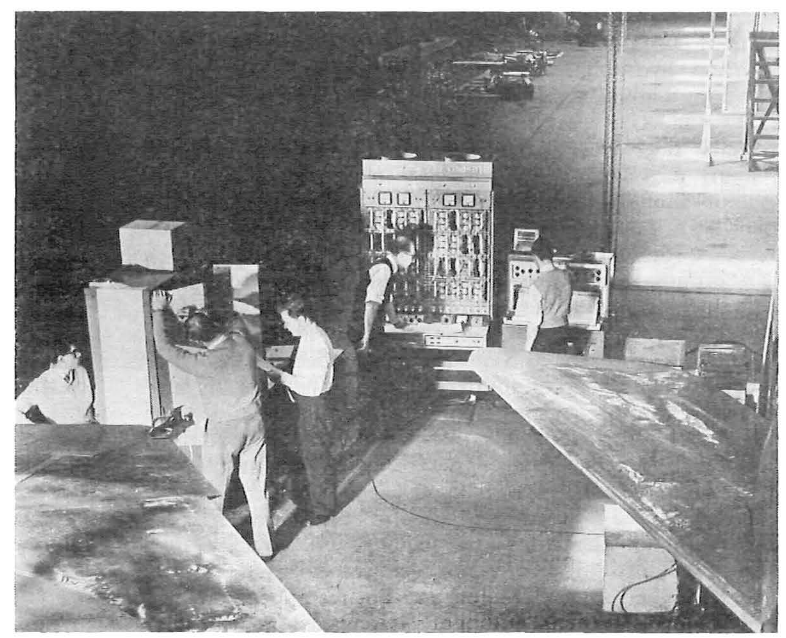


Figure 19. Dynamic response checking on a Lightning AFCS.

Figure 20. Lightning automatic flight control system.

limited authority and operated in the conventional way in "series" with the pilot's controls so that continuous demands could be injected into the flying control surfaces without the knowledge of this being conveyed to the pilot through movement of his manual controls.

A different approach was necessary for the "autopilot" or "outer-loop" controls. Before the introduction of the new hydraulic power actuators the main means of coupling autopilot demands to the controls was merely to connect the servometer, via a remotely operated clutch, directly to the cables or rods in the manual flying controls system. This was so-called "parallel" coupling as any movement imparted to the control runs appeared both on the flying surfaces and also on the pilot's controls, thus serving the double role of automatic control and monitoring indication. The clutch connection normally incorporated some force limit break-out action for safety if the autopilot suffered a runaway failure, so that by gripping the stick, the pilot could override the system if he so desired.

When hydraulic power controls with relatively low force inputs were introduced (the de Havilland Comet and the Boeing XB-47 were two of the first) there was the necessity to give the pilot's controls an artificial feel, and to many engineers it seemed wasteful that the autopilot actuator should continue to be inserted in the conventional way, requiring a high output capability merely to overcome the large "artificial feel" forces.

A proposal was therefore made for autopilot actuators to be integrated with the power controls. It seems that the main inventions involved simultaneously arose in both England and the United States, and it suffices to say that a very large number of military and commercial aircraft types now use the basic principles involved. These include currently the Buccaneer and VC10 in England, and the McDonnell Douglas Phantom and DC-10 in the USA. The version designed in England by Elliott Brothers (London) Ltd in 1953[62] was arranged to operate in two modes (Fig. 21). When the aircraft is being flown manually any stability augmentation demands are fed to the control surfaces in the "series" fashion and do not appear on the pilot's controls. When "autopilot" is engaged a means is provided to substitute an electrical output position feed-back for a mechanical one on the main output power controls. This allows electrical demands from the autopilot to be fed directly into the power controls, while maintaining "force limiting" for safety, by allowing the output demand to react against the artificial feel. It can be seen that the pilot's controls are then activated by the output power of the main hydraulic control, and any inherent backlash is therefore outside the main auto-controls loop, which solves another headache for designers. This is in fact a very elegant solution to all the problems involved.

16. AUTOMATIC LANDING

Automatic landing as a prelude to "blind landing", had been in the minds of designers and operators from the earliest days of powered flight. Simple procedures on selected aeroplanes did achieve "pilotless" landings from time to time, as already recounted.

The first attempt to design a complete three-axis automatic landing system was made by Siemens just before the Second World War[63]. For azimuth control, they automated one form of the instrument procedure used at the time for low visibility instrument approaches, which involved a sequence of procedural turns over a pair of vertical radio beacons. A radio distance measuring device, offset from the centre line, was also used (Fig. 22). The operation evolved around the careful programming of the DK 12 three-axis autopilot, and the radio azimuth landing addition was known as the "B. L. Tochter" (Blind Landing Daughter). In pitch the system used a radio altimeter (Mk 101) from which was generated a height plus height rate demand to effect an exponential flare-out to touchdown.

In the late summer of 1941 at Diepensee near Berlin, Paul Edward Köster carried out a deliberate series of take-offs and landings in fog, using the Siemens automatic system. He commented after ". . . . und damit ist das Problem der Blindlandung gelöst! (". . . and so the problem of blind landing is solved!")

History shows that it was not in fact to be solved that early. Captain Köster's landings were done in a low performance aircraft on a grass field. The ultimate requirement would be for high accuracy, highly safe landings on relatively narrow runways. The pressures of the war limited further work by Siemens.

There then followed the combined work of the USA and Britain at Defford, already described, and in 1946, the formation in the RAE of the Blind Landing Experimental Unit under the leadership of H. R. Pritchard as Superintendent and Wing Commander F. C. (Griff) Griffiths as

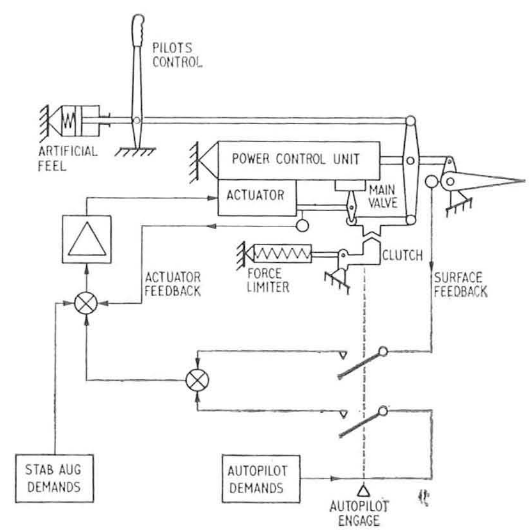


Figure 21. Elliott integrated power control concept: 1953.

Commanding Officer RAF. The BLEU was directed to concentrate a considerable effort on to the solution of blind approach and landing.

To BLEU goes overwhelmingly the credit for bringing to fruition the basic system for making accurate landings on runways, the concept of which is now in everyday use in both military and civil transport aircraft. Automatic "flareout" on runways was first demonstrated by BLEU in 1947. BLEU chose the "automatic" path to the achievement of blind landing, their philosophy being that the highest repetitive accuracy could be achieved by this means, as compared with alternative instrument guidance methods. This was a revolutionary and, with many pilots, an unpopular concept.

The Smiths Mk 9 autopilot, with extensive additions, formed the basis of the original BLEU experimental systems. Automatic coupling to localiser and glide slope ILS beams, as developed for auto-approach alone, comprised the first phase of an automatic landing, and the final approach and landing evolved around the use of a special magnetic leader cable pair, embedded on either side of the runway for accurate azimuth control, and a programmed radio altimeter demand for pitch control. The leader cable system was originally installed for measurement purposes only, and subsequently it was discarded for in-service use and substituted by an improved ILS localiser.

In October 1958 the BLEU announced that they had completed over 2000 fully automatic landings, on several different aircraft, and they released the results of their work to the commercial world.

The BLEU work showed how automatic landings could be achieved with high repetitive accuracy, but the failure

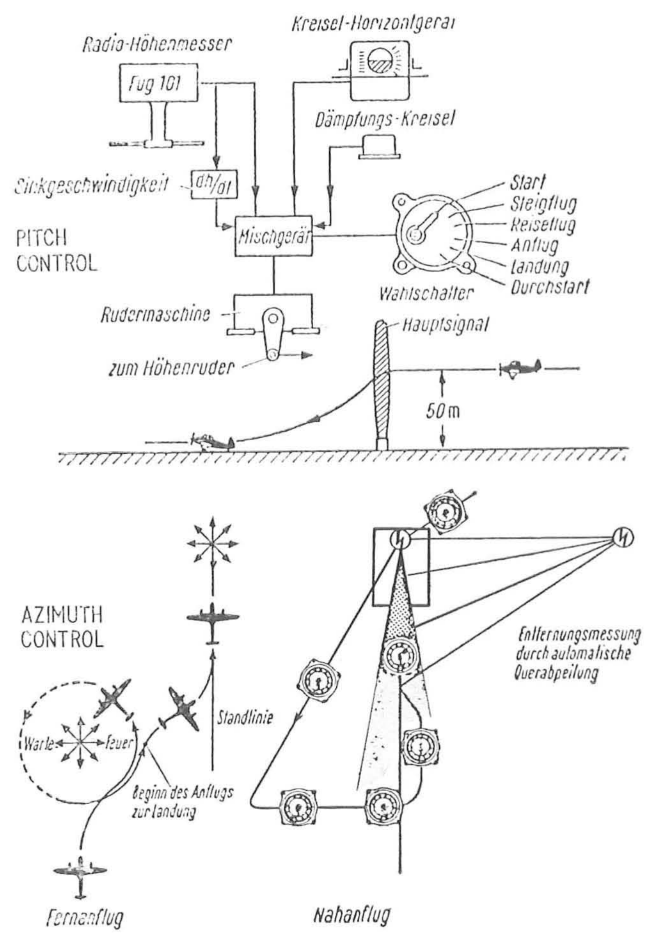


Figure 22. Siemens automatic landing system: 1941.

probability of such a system was too high for civil transport application. There would need to be an alternative recovery capability in the event of a failure occurring in the system during a landing. The British view was that the possibility of pilot takeover on instruments could not be seriously considered, as suitable instruments were not available, and in any case the ability of the pilot to perform such takeovers in poor visibility, with the requisite degree of success, could not be proven by any practical means. It was therefore decided that protection against the effect of failures should be provisioned by adding further automatic systems, and hence various "failure-survival" or "fail-operative" techniques were investigated[61].

At the time there were two companies in England who had orders for new transport aircraft; de Havilland were designing the Trident for BEA, and Vickers Armstrongs the VC10 for BOAC. Both airlines decided to incorporate provision for automatic landing from the inception of design.

By this time other blind landing experimental activities were also under way, mainly in the USA and France. By 1958 the Boeing 707, Douglas DC-8 and the Convair 880 jet transports were in service and the main pressures were applied to produce "add-on" blind landing capability to the existing installations. As the single-lane autopilots in these aircraft could not achieve an automatic fail-operative capability without extensive additions, the main approach became the so called "pilot-in-the-loop" one. This required continuous pilot involvement in the automatic operation, including the ability to assist the autopilot to correct obvious undesirable deviations during the approach and landing on the basis of instrument monitoring.

The United States manufacturers, operators and federal administrators all expressed doubts that the British approach to the blind landing problem would find universal acceptability. It was obvious that the amount of redundancy envisaged would greatly increase the price of the autopilot installation, and also the radio, instrument and related ground guidance system aspects.

In the event, many non-redundant system extensions aimed at all-weather operation were devised in the USA and installed in existing US transport jets, but little progress was made by these towards the achievement of blind landings.

One system using only a single landing autopilot with "safety monitoring" backed by the capability of pilot takeover in an emergency did however come into service. This was developed jointly by Sud Aviation and Lear-Siegler for the Caravelle and ultimately became the first aircraft to perform automatic landings while carrying fare-paying passengers. It is said that this achievement owed a great deal to the easy handling and relatively gentle landing characteristics of the Caravelle.

The pressure for blind landing in Europe in the late 1950s owed much to the frequent occurrence of low visibility, especially in London, and the desire to improve scheduled time-keeping determined BEA and BOAC to proceed with the development of the automatic landing systems which were provided for in the basic designs of the Trident and VC10.

However the designs of these two systems were approached from different viewpoints. BEA required the Trident for short-haul operations in Europe. They made a large number of their landings at London Airport and relied upon getting their aeroplanes back to their London main servicing base in order to ensure the regularity of their operations. For BEA therefore, automatic landing was to be a very important requirement. De Havilland and Smiths then set out to design an automatic system based on a triplex failure-survival concept. The Trident was to be an aeroplane in which crews would feel sufficiently at home in an automatic environment to allow the aircraft to do blind landings when this ultimate development stage was reached.

In BOAC the requirements were very different. BOAC is a long haul airline, and the VC10 was required for the "hot and high" routes. BOAC's prime requirement was to be able to send a VC10 around the world and, without any en route equipment changes, have a good probability that it would arrive back in London with all systems services still available. This could only be achieved with a fair amount of on-board equipment duplication. Hence the concept of a dual autopilot installation in the VC10 was born.

However a basic dual installation of this sort would not include enough information to give the automatic failure survivability required for all-weather landing, but as this was not so vital to the type of operation envisaged by BOAC, it seemed for a time that automatic landing might not finally be pursued on the VC10.

However another factor entered. It was the custom in post-war autopilot design to limit the authority of the systems to safe levels by imposing a maximum fixed torque limit on the servo outputs. This was normally set to a level which prevented overstressing or over-manoeuvring the aircraft in the most sensitive parts of the flight envelope, while at the same time allowing sufficient authority in the low speed, forward cg condition, especially during approach and landing. The Trident and the VC10, and their US contemporaries for that matter, were intended to operate at relatively high subsonic Mach numbers, and even when the mitigating effect of artificial feel was included it was difficult to achieve a satisfactory single setting for the torque limitation at the autopilot pitch servo coupling point. Hence the systems needed further protection to ensure that excessive automatic demands could not be imposed on the airframe following any autopilot failure.

Smiths and de Havilland achieved this on the Trident by virtue of its triplex system philosophy and did not use mechanical torque limiters.

The VC10 retained the torque limiter philosophy based upon the Elliott integrated hydraulic principle, but Vickers Armstrongs required this to be supplemented with additional electronic monitoring. This was first attempted with a single extra monitor channel, to serve both of the autopilots. This would have been a simple extension of the concept of the Boeing 707 autopilot, the Bendix PB-20D, which was already in service with BOAC, and which was selected to be the basis upon which Elliott would design the VC10 autopilot system. Unfortunately the single monitor concept, although simple at first glance, proved to be far too complicated to implement in practice. Hence two separate monitors were chosen, this giving rise to the Elliott duplicate-monitored autopilot for the VC10, with automatic changeover following a failure, and the concept of dual-dual systems later to be used in the transport aircraft produced by a number of manufacturers. The VC10 system then had the basic capability to survive any single failure, as had also been provided by the triplex system in the Trident, and it therefore also became capable of performing failure-survival automatic landing[65] (Fig. 23).

So much has been written about the detail of the design of these systems over the past 15 years that it is worthwhile here only to outline background philosophies and to state what their contributions are to the evolution of automatic flight controls. Perhaps the most significant aspect of the design technology was that both systems were transistorised to the greatest extent possible within the limits of the components available. The VC10 system in particular used most of the existing Bendix PB-20 modules. These were elegant metal cards with "punch-through" terminals which allowed a very economic wiring assembly. At this time the use of largely immutable printed circuit boards was not favoured for automatic pilots, due to the unavoidably large amount of modification which

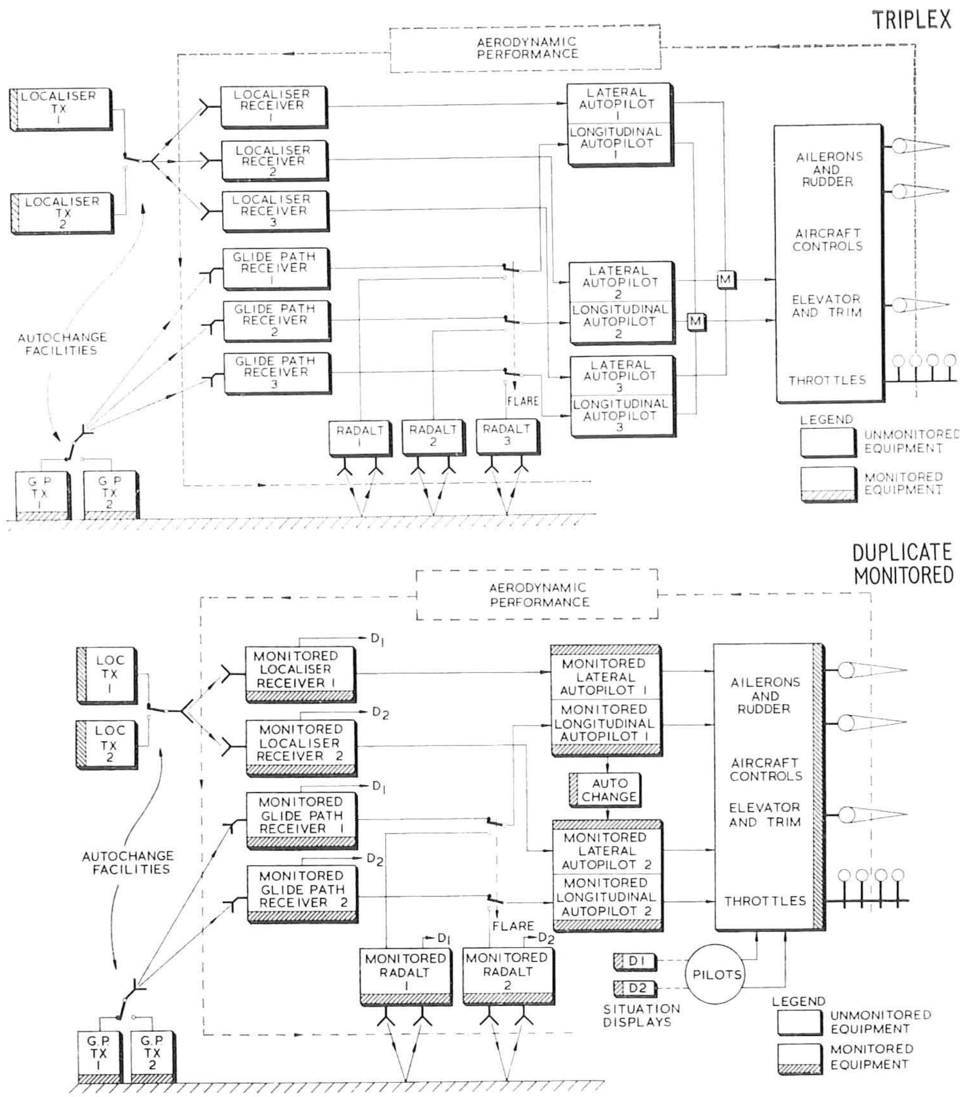


Figure 23. Failure surviving automatic landing systems.

was demanded in the later stages of flight testing. The PB-20 concept was developed under the leadership of Paul Noxon of the Bendix Eclipse-Pioneer Division at Teterboro, New Jersey.

A major hurdle for the Trident and the VC10 automatic landing systems was certification. These were the first aeroplanes required to rely to some extent upon electronic systems for safety in the critical landing stage of flight. Certification therefore had of necessity to be based partly on statistical analysis of the redundant equipment installations, as it was impossible to carry out sufficient test flying to prove the levels required in practice.

The certification requirements were evolved from around 1960 by the Air Registration Board who laid down that any automatic landing system, in whatever visibility condition it was used, would need to be at least as good as manual landing in good visibility, or preferably an order of magnitude better. The so called "1 in 10^7" requirement as the maximum probability of a fatal landing accident under automatic control was thus created and became the criterion for certification[66].

The automatic landing system concept as generated in England also embraced the associated ground guidance equipment and airport facilities and therefore demanded a total systems approach to safety and regulations. Her Majesty's Government tackled the problem which this posed with the formation of a special Ministry Directorate of All-weather Operations which was later incorporated into the Civil Aviation Authority.

In the Trident airborne design Smiths employed a triplex electric autopilot philosophy, using triplex sensors, triplex computing and triplex electrical servos. This matched the aeroplane in concept, which has three engines and three electrical systems.

The VC10 is a four-engined aircraft, with four electrical systems, and elevator and aileron surfaces each split and powered in four sections. To match this Elliott used automatic control elements in combinations of two or four.

In the evolutionary cycle of automatic flight controls the Smiths' system was the world's first fully triplexed automatic landing system and the VC10 monitored-duplicate philosophy spawned the idea for subsequent dual-dual systems and their attendant self-monitored sensor devices. Throughout the world there are now available self-monitored radio receivers, self-monitored radio altimeters, self-monitored air data computers and so on. Such devices are widely used on the present new generation of civil transport aircraft.

The pitch control (autoflare) aspect of the Trident automatic landing system was introduced into service in June 1965. (A comprehensive history of the development was presented by K. G. Wilkinson in the Royal Aeronautical Society Geoffrey de Havilland Memorial Lecture in 1969[67].) The Trident has to date performed over 20 000 automatic landings in passenger service and is cleared for Cat 3A operations to visibilities less than 300 metres RVR (Runway Visual Range) and down to 12 feet decision height from touchdown. The VC10 has had a Cat 3A equipment installation in service since 1968 but is cleared only for Cat 2 automatic landing, having performed considerably less landings than the Trident.

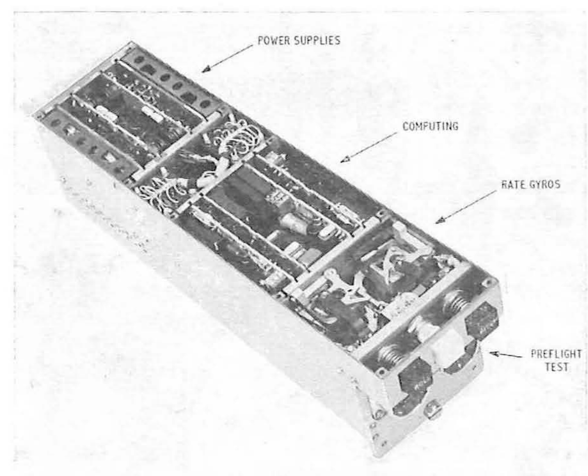


Figure 24. Harrier autostabiliser: Pitch and roll axes.

17. REDUNDANCY, MICROCIRCUITS AND DIGITAL COMPUTING

The decade of the 1960s will go down in history as a prolific one in the history of automatic flight controls. It has seen the adoption of the technology of the space age, particularly that of solid state electronics and the extension of autopilot responsibility to cover automatic landing in very low visibility. The use of redundant equipment for failure survivability also spread from the automatic landing application into other "safe" systems which can extend the operational and performance capability of most types of aircraft. So-called "fly-by-wire" systems are now being designed which will dominate the performance characteristics and handling of the aircraft which use them. ("Fly-by-wire" is the complete operation of the control surfaces from electrical signals derived from the pilot's manual controls and suitable motion sensor feedbacks from rate gyros, accelerometers and such like.)

The space age and its attendant developments has spawned the tiny microcircuit, which has revolutionised the computation capability which can be contained in a reasonable size of box. Indeed, the proliferation and relatively low cost of the digital microcircuit and miniature digital storage devices (memories) now available has bulldozed the AFCS designer, probably willingly, into the exclusive use of digital computing and data transmission techniques in new designs. Many automatic controls designs can now be implemented easily, which previously required great inventive skill, or were not done at all.

The progression in the use of these new key aspects in AFCS design is apparent in the various aircraft systems which were conceived in the 1960s or have come to fruition in recent years.

On the military side there were a series of NATO requirements which excited great interest in VTOL, and a great spate of powered lift designs were generated. In fact the activity in Europe was probably initiated by the development of gas turbines having thrust/weight capability significantly greater than unity, notably by Bristol Siddeley Engines and Rolls-Royce.

The last-named company in conjunction with the RAE demonstrated the "jet lift" capability with the so called "Flying Bedstead" in the early 1950s. This, of necessity, used a rate gyro automatic stabiliser which generated controlling moments in the hover by actuating pneumatic nozzles energised from engine bleed air. In 1954 Short Brothers and Harland Ltd commenced work on an experimental aeroplane using a similar concept, which was designated the SC1[68].

This was also designed on the concept that automatic stability would be essential and that hovering without assistance would either be impossible, or unacceptable to pilots. The automatic system used stick position, attitude, rate and acceleration sensors and rate actuated electrically signalled controls operating "puffer" nozzles on the aircraft extremities. The lift unit group comprised four RB108 engines which were also designed to be inclined fore and aft for deceleration control. There was also a single similar propulsion engine. The automatic system was triplexed (i.e. the three lanes were designed to be continuously in operation) with fault detection and manual lane isolation capability to cope with failures.

It was probably the first multiple redundant system, and incorporated one of the first manoeuvre demand systems, the stick movements giving no indication of control surface positions. This type of automatic control was made necessary by the severe handling problems which the design presented, especially laterally. The system used triplex hydraulic actuators, relied upon electrical comparison for failure detection, and did not have any mechanical tolerance absorption capability in the actuator itself, which is a feature of most modern counterparts. The SC1 was used extensively over a number of years for basic research on controls systems and VTOL handling development work.

Most of the jet lift VTOL designs of the 1950s and 1960s demanded the provision of failure-survival automatic controls as an essential feature of their flight. A notable exception of course is the HSA Harrier, the only design which has come to fruition as an in-service aircraft. The "inherent" versus "artificial" stability arguments which were pursued during the conceptual stages of this aircraft was history repeating itself, when the philosophical dichotomy between the two schools of thought on flight control at the turn of the century is recalled. However, the Harrier does carry an autostabiliser system. This is a simple, single lane, three-axis system giving short period stability enhancement in the conventional way by using rate gyros and accelerometers. Its special feature is its low weight (only 2½ lb per axis including sensors, computing and hydraulic servo power amplifiers). It also has an inbuilt automatic test capability (BITE) to allow first-line testing without the need for external ground test equipment (Fig. 24).

One elegant solution to the multiple redundant automatic problem which was produced during the VTOL NATO competitive period arose from a joint activity between the Italian Fiat Co., Rolls-Royce and Elliott, which resulted in the construction of a VTOL hover rig of the proposed Fiat G95/4 aircraft design. This combined the best concepts of duplicate-montitored sensors and computing, and multiplex hydraulic actuation.

The rate gyros were self-monitored, and rapid disturbance free changeover to the standby could be effected if a failure occurred in the driving unit. The quadruplex actuator force balanced its four hydraulic pistons via hydraulic "spring boxes" and hydraulic clutches on a common output shaft and was designed so that the disengagement occurred of any failed section on the basis of majority vote disagreement (Fig. 25).

The system rig performed about 300 hours of tethered flight tests and thoroughly proved both performance and failure survivability of the design.

Unfortunately none of the VTOL aircraft designs using failure-survival automatic controls were put into production, but a great deal of technology in automatic flight controls accrued as a result. For example much of G95/4 system development was continued after the Fiat rig testing and has contributed greatly to the design concept of the automatic flight controls system now chosen for the MRCA, which employs Elliott/Fairey quadruplex hydraulic fly-by-wire actuators (Fig. 26) integrated with the power controls.

The capability for building failure-survival, or fault tolerant systems, has also opened up the possibility on the military side for low level automatic operation in modes such as terrain following.

Such a capability was built into the British multi-role

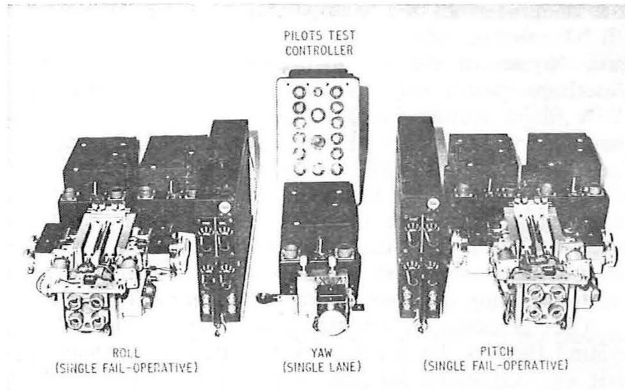


Figure 25. The Fiat G95–4 multiplexed hover rig system: 1964.

strike reconnaissance aircraft, the TSR2 (cancelled following a change in government in 1965), which had an Elliott AFCS of considerable sophistication, using triplex and duplex flight controls axes to meet a high performance and safety requirement. The system was very advanced, and employed concepts which only now are coming into general use. It was fully transistorised with a rate gyro and accelerometer actuated stability augmentation system. It received its attitude reference information from an inertial platform and manometric information from a central air data computer. The system had automatic terrain following, the control signals for which came from a forward looking radar. It also had ILS coupling, with automatic throttle control and the normal sophistication of the modern era in using such facilities as fully synchronised operation, automatic trim and integrated coupling to hydraulic controls (Fig. 27).

The very low weight of the Harrier autostabiliser system has been mentioned and this was achieved in the mid 1960s partly because of the new development of the integrated microcircuit. All military and civil systems are now microcircuit designs. However its earliest wide scale use for civil aircraft flight control was initiated in 1963 when, rather tentatively, the design of the Concorde SST system was based upon microcircuit technology (at that time a bold decision). Without this new electronics capability there is no doubt that the vast technical problems which the Concorde presented would not have been solved.

The automatic operation of the Concorde demands the solving of control and stability equations and mode logic which employ nearly 4000 microcircuit elements, about 2500 being analogue amplifiers and the remainder digital

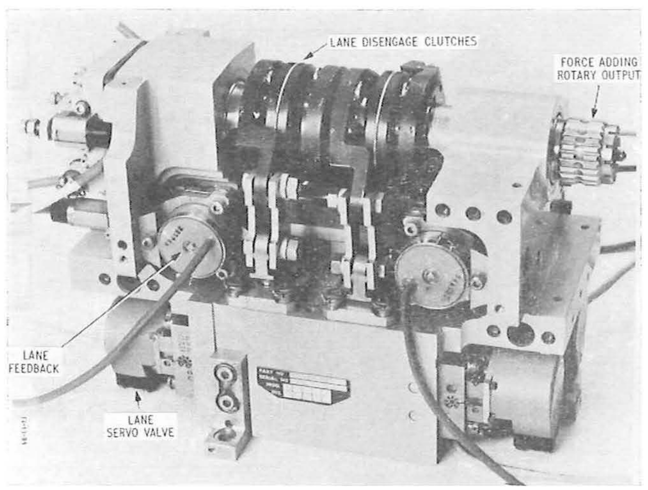


Figure 26. MRCA quadruplex actuator (Elliott/Fairey).

logic devices. Compare this with the 10 or 20 operational amplifiers used in the autopilots of the 1940s and 1950s, or the single pneumatic amplifier in one axis of the Askania course controllers of the 1920s!

The Concorde also carries two special-purpose digital computers used entirely for the purpose of programming the testing of the system and the locating of failures when they occur in the automatic flight control installation.

18. TODAY: THE SUPERSONIC AGE

The Concorde automatic flight Control system design is representative of the end point in the first 100 years of development and use of automatic flight controls, not only because of its technical detail, but because it arises in an era which is now not only the one of the "project management team" but also an era of international collaboration. Projects of such magnitude are no longer likely to be brought to fruition other than by drawing upon the resources of more than one nation.

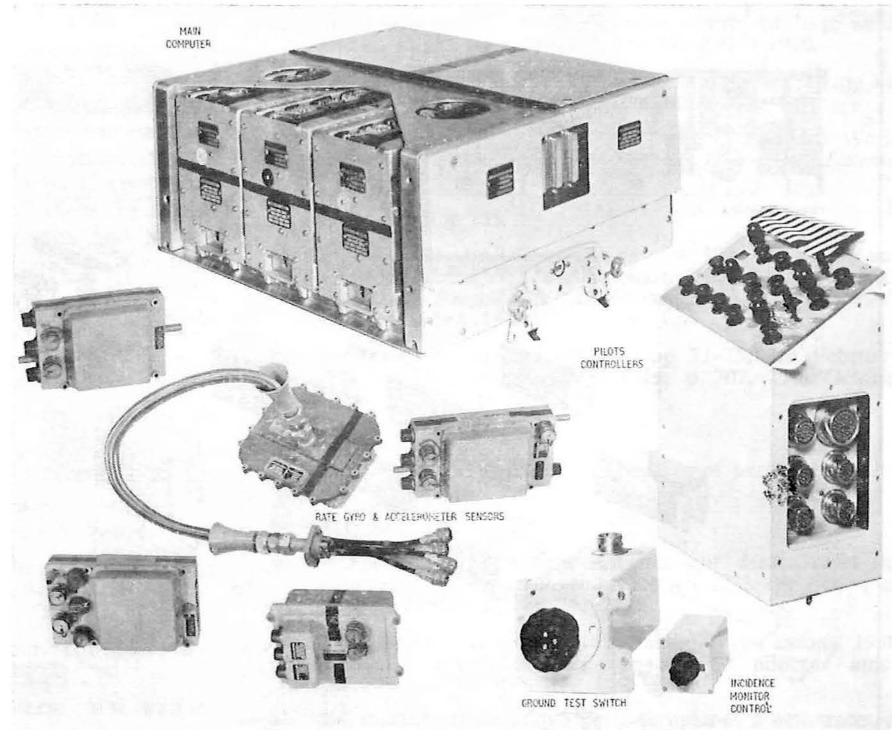


Figure 27. The TSR-2 automatic flight control system: 1964.

The Concorde AFCS is the product of a joint design effort by Elliott in England, SFENA (Société Française d'Equipements pour la Navigation Aérienne) in France, and during early development, also by the Bendix Corporation in the USA. This system is therefore worthy of some detailed description so that the reader is left with a final idea of the vast technological development which the world has seen over the past 100 years. It comprises six basic subsystems (Fig. 28).

(*a*) Autopilot and Flight Director
(*b*) Three Axis Autostabiliser
(*c*) Autothrottle
(*d*) Electric Trim
(*e*) Safety Flight Control
(*f*) Integrated Test and Maintenance

The autopilot is a duplicated-monitored one which provides automatic control from initial climb, through cruise, to automatic landing. Monitoring techniques ensure "fail-soft" operation in all modes with continuous automatic back-up by the second monitored control channel available during final approach and landing. The system incorporates a landing display giving serviceability information and in the event of an abort, automatic go-around is provided.

A three-axis stabilisation system operates directly into the elevon and rudder control surfaces without moving the pilot's controls, and it is arranged that automatic rudder demands are applied to limit sideslip following any engine failure. The three-axis stabilisation system is also self-monitored and duplicated.

An important control system is the automatic throttle, which can operate to give accurate control of airspeed or Mach number. A separate system is also incorporated to monitor the effect of high incidence flight, and will act to give warning and also activate the controls if certain limits are exceeded. Both of these are duplicate-monitored systems.

The complete Concorde electronics is packaged into eight types of computer unit, each being duplicated. These are:

(i) Autopilot & Flight Director Pitch Computer
(ii) Autopilot & Flight Director Azimuth Computer
(iii) Autos abiliser Computer
(iv) Autothrottle Computer
(v) Electric Pitch Trim Computer
(vi) Warning and Landing Display Computer
(vii) Safety Flight Control Computer
(viii) ITEM Computer (Integrated Test and Maintenance)

The electronic implementation is based upon linear computing elements and digital integrators, and associated external components to set gearing transfer functions. The circuits are arranged on stacking modules which mount into the sides of the boxes, which themselves provide physical segregation between "command" and "monitor" computing areas to preclude the possibility of common failures. Solid state logic switching circuits are isolated inside a common central spine. All computers have digital inbuilt test facilities which can be activated by means of a parallel digital data highway from the ITEM computer, the result being displayed on the flight deck. This BITE system has been limited in complexity so as not to increase the system MTBF (mean time between failures) of the total system by more than 15%.

A great deal of attention has been paid to pilots' controllers for the Concorde AFCS. The systems required to be engaged throughout the flight are in a special guarded engage switch unit located in the roof panel and all mode selection and autopilot manoeuvring controls are on a pilot's control unit in the centre of the flight deck immediately below the glare shield.

There are no less than 33 modes of operation available from the Concorde AFCS. Apart from the conventional ones the system has a Maximum Operating Mode (MAXOP), this single mode controlling the aircraft

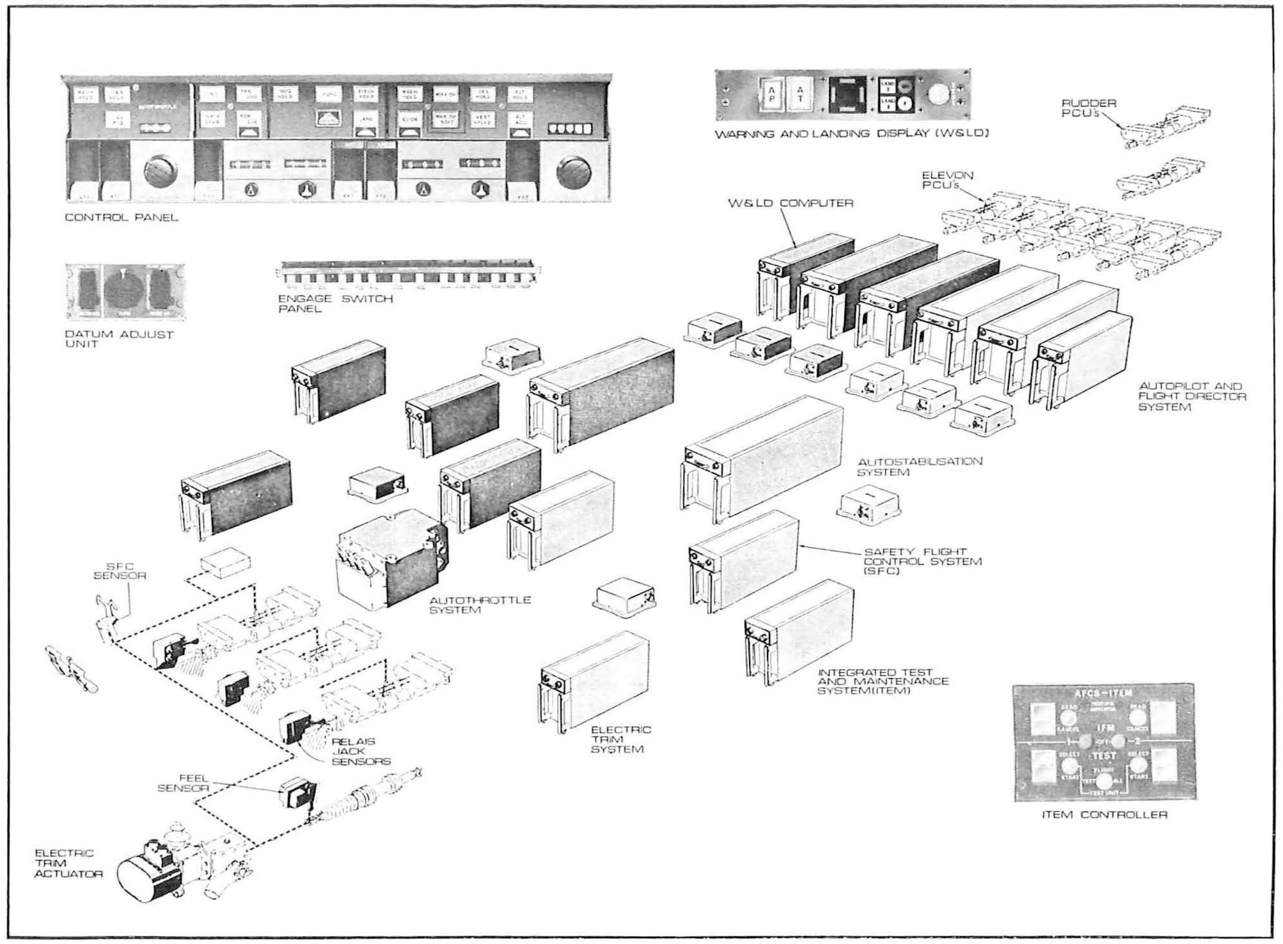


Figure 28. The Concorde SST automatic flight control system.

acceleration from 5000 feet to the supersonic cruise altitude within the limiting flight envelope of Mach number, speed or temperature.

Automatic landing is selected by a single push button operation. This initiates all capture and approach hold functions and causes full in-flight testing of the all-weather system to be done prior to settling in to the final approach. The system uses a progressive introduction of interlocks and a tightening of monitoring thresholds as the altitude is reduced.

The total Concorde system described weighs 365 lb (166 kg) of which 70% is electronic boxes (almost the same weight as a two-axis Aveline stabiliser of the 1920s). The Concorde system is representative of the most advanced equipments available and in service today.

19. CONCLUSION

It can be seen that over a period of 100 years the design of automatic flight control systems in fixed wing aircraft has escalated in the same manner that has epitomised the growth in other fields of engineering technology. The pattern is irregular and it is doubtful if, one hundred years from now, the future evolution will show any more regularity than it has in the past century. Most of what exists at any time, especially in the field of electronics, is the product of the period immediately preceding it, from only a few years back in general.

As with natural evolution, there are periods of steady development which are uplifted bodily from time to time by massive mutations.

Undoubtedly the major recent mutation in the history of automatic flight controls, as in many areas of technology, was the discovery of the semiconductor and its development to the microcircuit, not only because of its amplifying and logic capability, which merely duplicated other devices, but because of its simplicity, small size, reliability, and ability to fit the AFCS environment. Electronic devices are now fast approaching the stage where their manufacture is as automatic and repeatable as the materials from which airframe structure is made.

It is hard to envisage what the next mutation might be. There is now a rapidly evolving activity in the complete application of digital processing to automatic flight control systems, and most new designs follow this basic route. Miniature airborne computers can now be constructed which can handle data at a rate of several million instructions per second and it is now also certain that in the future, data will be widely transmitted around aircraft on small numbers of optical fibre cables, signals being coded and multiplexed light emissions, rather than electric currents in a multitude of copper wires, which are so heavy and susceptible to electromagnetic interference, short circuits, etc.

It is already expected by some that the performance characteristics of aircraft designs of the future will be completely dominated by the sensor, computer and automatic controls aspects, perhaps even to the extent that they will completely rely upon them, as part of the overall safety inherent in the design of the complete vehicle.

Perhaps the coming age of such aircraft, so called Controls Configured Vehicles (CCV) will see the ultimate vindication of the era of Sir Hiram Maxim and those of his contemporaries who pursued "artificial" stability solutions to the problem of mechanical flight.

20. ACKNOWLEDGMENTS

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