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AUTOMATIC STABILIZATION

By Fr. Haus

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I. INTRODUCTION TO THE STUDY OF AUTOMATIC LATERAL STABILIZERS*

1. Object of This Study

A few years ago we took up the study of the principal longitudinal automatic stabilizers that were known to us at the time. Although our study was limited to the maneuvers of the altitude control, it nevertheless brought out clearly the principle of automatic piloting which may be stated in the form of a postulate, as follows: Since instrument flying has become a matter of actuality, it should be possible to define in a nonequivocal manner the motion to be given to the controls in accordance with the indications of certain board instruments. Having once established this program, it is a relatively simple matter to contrive the automatic apparatus which will bring this result about.

We feel ourselves justified in taking up again the study of automatic stabilizers, extending it to the general case which includes the control of the three-control system of the airplane. There are numerous reasons which justify us in the work we have undertaken: (1) Important contributions have been made to the theory of instrument flying; L'Aéronautique has published several papers on this subject. (2) There is no doubt that the time for the practical application of automatic control has arrived. In the United States the usual equipment of certain types of transport airplanes includes an automatic stabilizer. In several European countries there are airplanes using complete automatic control which are able to fly effectively and even to take off and land without the intervention of the pilot. (3) The number of different schemes proposed for obtaining stability or automatic piloting is constantly on the increase. We believe it will be of benefit to investigate the different solutions that have been used or

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that have been seriously considered with the object of systematizing and classifying them.

Our study will of course be incomplete since the work done on automatic piloting is generally held confidential and the literature we have been able to gather on the subject, although extensive, nevertheless remains incomplete.

2. Lateral Disturbed Motion

The point of departure in our study of automatic flying is the mathematical analysis of the disturbed motion of an airplane. Before deciding what forces to apply to an airplane in order to fix its trajectory, it is necessary to know how the latter would behave as a result of an external disturbance if the airplane were left to itself with controls blocked. The analysis of the dynamic stability of a rigid airplane is therefore the basis for the study of automatic piloting.

We have given in the preceding articles a résumé of the method by which the study of longitudinal motion may be approached. This method is equally applied to rolling as well as yawing motion. These motions are inseparable, the one from the other, and they are always accompanied by sideslipping. The simultaneous study of these phenomena is at the basis of the analysis of lateral stability. For a detailed study of the latter, we refer to special works on the subject and we shall content ourselves with summing up the problem briefly.

Let us take as our axes OX, OY, OZ, fixed in the airplane, and the definitions previously given for the linear speed V, and angular speed Ω, denoting the resulting force by F and the moment by C. (See fig. 1.) L and N will denote the aerodynamic moments about the OX and OZ axes and F_Y the resultant of these forces parallel to the OY axis. The position of the airplane in space will be determined by the orientation of the OXYZ system with respect to the system $OX_0Y_0Z_0$, regarded as fixed with OZ_0 vertical. The position of any set of axes with respect to another is always determined by three angular magnitudes. These will be denoted by ψ, θ, φ, shown in figure 2.

When the study of longitudinal stability is considered apart from that of lateral stability, we need consider for the latter case only the two angles φ and ψ, which correspond approximately to lateral inclination and and azimuth. The rotation ψ, takes place about a vertical. The angle ψ, has the following important property: Whatever the final position of the axes, the projections of the weight on these are independent of this rotation. The motion of the airplane will be defined by its angular velocity about the OX and OZ axes and by the projection of the aerodynamic velocity V, of its center of gravity, on the OY axis. With a given velocity V, the position and motion of an airplane are defined as far as the lateral motion is concerned, by five variables v, p, r, φ, and ψ, and the longitudinal motion is entirely defined by four, u, w, q, and θ. We may note that the position of the airplane on its trajectory is defined by the angles of incidence i, and of yaw j, which may be written when the angles are small, $i = -\frac{w}{u}$, $j = +\frac{v}{u}$, or $i = -\frac{w}{V}$, $j = +\frac{v}{V}$ (fig. 3).

It is possible to write down the following five equations for the lateral motion, namely: An equation of equilibrium for the forces along the OY axis in which the linear acceleration $\frac{dv}{dt}$ enters, two moment equations about the OX and OZ axes, in which the angular accelerations $\frac{dp}{dt}$ and $\frac{dr}{dt}$ enter, and two geometrical equations connecting the angular velocities p and r with the derivatives $\frac{d\varphi}{dt}$, $\frac{d\psi}{dt}$. We then have as many equations as there are variables and the system may be treated in the same way as the equations defining the longitudinal equilibrium.

The motion arising as a result of any disturbance whatever, δv, δp, δr, $\delta\varphi$, and $\delta\psi$ may be determined, but the solution depends after the integration of the differential equations upon an algebraic equation of the fifth degree in λ instead of an equation of the fourth degree. Here an important fact should be considered. In the study of longitudinal motion we find that certain components of the external forces depend on the angle θ. When θ is not 0, the axis of the airplane is inclined upward or downward with respect to the horizon, and the weight has a component along the OX axis which either adds to or subtracts from the pull of the propeller. When the airplane is dynamically stable it returns to its initial state after a series of oscillations. The forces acting on it should then regain their initial value. This result cannot be obtained unless the airplane resumes its initial longitudinal position θ.

In the study of lateral motion we consider two angular magnitudes φ and ψ. The component of the forces along the OY axis depends on the angle φ since the weight has a lateral component when the airplane is in an inclined position. If the airplane is dynamically stable, it returns after some slight disturbance to its initial position and should then regain its angle of inclination φ. The case is different when we consider the angle of ψ. Whatever may be the final position of the axes fixed in the airplane, the components of the weight on these axes are independent of the rotation ψ. There is no force or moment that is a function of the azimuth. Therefore, when an airplane in dynamic equilibrium returns after a disturbance to its initial state, it should regain a motion that is characterized by the same speeds and angles φ and θ, that it had originally, but not necessarily the same angle ψ. The airplane after the disturbance no longer follows the same azimuth as before. The airplane possesses no directional stability, all derivatives with respect to ψ, the external forces and moments being 0. This anomaly is met again in the computation in the form of a particular solution of the characteristic equations. The fifth-degree equation in λ always yields, in fact, a solution $\lambda = 0$. This circumstance facilitates the analysis since the characteristic equation becomes of the fourth degree when this solution is eliminated, and the mathematical analysis of the lateral motion is then made by methods similar to those used in the study of ~~lateral~~ long. motion.

The absence of directional stability in the motion of an airplane is important. The existence of the static rolling and pitching stabilities are not sufficient to compensate for its absence.

3. Static Stability

Static stability is that phenomenon as a result of which a restoring moment arises whenever the airplane suffers a displacement with respect to its trajectory. Displacement of the airplane from its trajectory shows itself as far as lateral motion is concerned in the angle of sideslip j. The sideslip arises whenever the aerodynamic speed V, departs from the plane of symmetry of the airplane. The sideslip will give rise to two moments L and N (fig. 4) about the OX and OZ axes situated in the plane of symmetry. These moments L and N are given as functions of the linear dimensions of the airplane through the coefficients C_L and C_N,

$$L = C_L \; S \; b \; \frac{aV^2}{2g}$$

$$N = C_N \; S \; b \; \frac{aV^2}{2g}$$

The wing spread of the airplane will by convention be taken as the reference length b. The derivatives $\frac{\partial C_L}{\partial j}$ and $\frac{\partial C_N}{\partial j}$ determine the static stability of the airplane. They are, respectively, the rolling and yawing coefficients of stability. It is easy to see that (1) $\frac{\partial C_L}{\partial j}$ is positive when the effect of the lateral surfaces of the airplane situated above the OX axis is greater than that of the lateral surfaces beneath the axis. (2) That $\frac{\partial C_N}{\partial j}$ is positive when the effect of the lateral fin surfaces in the rear predominates.

The form of the wings is a strong factor in the lateral static stability. Increase in the dihedral produces an increase in $\frac{\partial C_L}{\partial j}$. The camber increases $\frac{\partial C_N}{\partial j}$. These coefficients may be evaluated and numerical values obtained. Experiment shows that the moments L and N, depend each on the angle of attack so that it is always necessary to specify in giving a numerical value, to what angle of incidence it corresponds. An airplane is statically stable as far as yawing motion is concerned if it tends to line up with the wind direction, which is the case when $\frac{\partial C_N}{\partial j} > 0$. As far as rolling is concerned, one cannot tell a priori whether the stability corresponds to a positive or negative value of $\frac{\partial C_L}{\partial j}$. An investigation is, in fact, necessary to determine, when the velocity deviates from the plane of symmetry, whether it is preferable to allow a rotation about the OX axis in one sense or the other. Dynamic phenomena enter into play here. (See fig. 5.)

Before the great war Captain Duchene had shown that if the mass in an airplane is distributed so that the principal longitudinal axis of inertia rises from front to back, the condition $\frac{\partial C_L}{\partial j} > 0$ may correspond to stability. This tendency, however, is counterbalanced by another phenomenon, and one may say that it is better in the great majority of cases, when a positive sideslip angle $+j$ arises, for rotation in the positive sense about the OX axis to be set up rather than a rotation in the negative sense. Let us examine what takes place when the airplane is accidentally deflected and undergoes an initial displacement $\delta\varphi$. Let us assume that the airplane deflects to the left, $\delta\varphi < 0$. With the airplane deflected the equilibrium of the force components along the OY axis is disturbed. The weight now has a component on this axis and a lateral gliding motion toward the direction of inclination of the airplane is produced. This motion is governed by the first of the equations for lateral motion,

$$\frac{p}{g}\frac{dv}{dt} = F_Y - p \sin \varphi$$

There will then be a displacement δv; for $\delta\varphi < 0$ the displacement δv produced is greater than 0 and corresponds to $\delta j > 0$. But this yawing in its turn produces a restoring moment; if $\frac{\partial C_L}{\partial j} > 0$ a displacement $\delta j > 0$ produces a positive moment δL, which tends to restore the airplane. We see that the lateral stability is not, properly speaking, a static stability. A lateral inclination $\delta\varphi$ does not directly produce a restoring moment δL, but only indirectly through the intermediary of the dynamic phenomena brought about by the yawing which is the immediate consequence of the lateral accidental deflection.

4. The Combination of Rolling and ~~Pitching~~ Yawing

Static Stability

Dynamic theory indicates that we cannot assign arbitrary values to the coefficients of stability. $\frac{\partial C_L}{\partial j}$ and $\frac{\partial C_N}{\partial j}$. If the conditions $\frac{\partial C_L}{\partial j} > 0$, $\frac{\partial C_N}{\partial j} > 0$ are fulfilled without stopping to consider any further the resultant motion, it may appear that the airplane will be incapable of flying in a straight line. When the airplane leans to the left, it does so under the action of its weight and the displacement $\delta v > 0$ will really have two effects: (1) The airplane will have a tendency to restore itself under the action of $\frac{\partial C_L}{\partial j}$; the yawing to the left will tend to incline the airplane to the right. (2) The airplane will have a tendency to bank to the left since it behaves like a wind vane, $\frac{\partial C_N}{\partial j}$ being positive. There then arises a new disturbance, a rotation $\delta r > 0$. In this motion the right wing will be on the outside and will be displaced more quickly than the left. The lift will be stronger; it will tend to rise still further, that is, accentuate the lateral deflection. The moment L, is, in fact, a function of r. The derivative $\frac{\partial C_L}{\partial r}$ is negative and the displacement δr has a tendency to restore the exterior wing which in this case is the right wing.

Two opposed effects are produced and one or the other will predominate according to the structure of the airplane. If the effect of the static stability of rolling is greater, the airplane may, after turning, regain its initial state. It will, however, fly in another direction than that which it had before the disturbance $\delta\varphi$. If the effect of the angular velocity r, on the rolling moment is greater than the effect of the displacement j, the second effect will predominate. The deflection of the airplane will increase and the airplane will describe a spiral trajectory. It is then dynamically unstable. In spite of the static yaw and rolling stability, it will possess a spiral instability because the first type of stability is too great in comparison with the second.

Airplane constructors seeking to improve the straight-line flight characteristics of an airplane have, with good intentions, been increasing the fin surfaces. As a result they have achieved just the opposite effect. They have either produced or accentuated spiral instability. This paradoxical fact shows the complexity of the problem.

The study of the effects of yawing explains certain differences that occur in the piloting of airplanes. Airplanes which have a tendency to spiral instability can easily be put into a spin by the action of the wings alone. In fact, the voluntary lowering of one wing may put the airplane into a spin as a result of a series of phenomena described below. If the airplane possesses, on the contrary, the opposite characteristic - that is, a large lateral stability compared with yaw stability - it can steer almost the correct amount by the simple action of the rudder. Let us assume that we wish to turn to the left. On setting the rudder for this direction a rotational movement about the OZ axis is imparted to the airplane. Without having its trajectory modified at first, the front of the airplane is displaced to the left of the vector V so that the airplane yaws to the right δv and $\delta j < 0$). The lateral stability then comes into action, inclines the airplane to the left ($\delta L < 0$), and as a result of the initial yaw displacement, the airplane is more or less correctly restored to its initial position. We shall see farther on that an airplane whose lateral stability is too great compared with its yaw stability is likely to undergo a continual side swinging.

The preceding remarks show us that the present tendency of popular builders of airplanes to suppress one of the side controls is not entirely unjustified. But those builders who seek to simplify piloting by omitting the rudder, and steering by means of the ailerons alone may quite realize their object, provided they properly proportion the yaw and rolling stability.

It is evident that the "Pou-du-Ciel" of M. Mignet has the proper lateral stability to enable it to steer correctly by means of its rudder with but little sideslip.

5. The Mathematical Theory

Having shown several aspects of the study of lateral motion, we may now briefly glance over the results of mathematical analysis. The classical method requires a knowledge of the derivatives of the aerodynamic forces and moments with respect to the linear and angular speeds. Let us first examine the derivatives of the moments. The derivatives $\frac{\partial C_L}{\partial v}$ and $\frac{\partial C_N}{\partial v}$ = respectively, $\frac{1}{V}\frac{\partial C_L}{\partial j}$ and $\frac{1}{V}\frac{\partial C_N}{\partial j}$, and are proportional to the coefficients of static stability defined above. The derivatives $\frac{\partial C_L}{\partial p}$, $\frac{\partial C_N}{\partial r}$ are the derivatives of the moments with respect to the angular velocity about the same axis. They are the damping coefficients; they are negative when the resulting forces tend to damp the motion, positive if they tend to increase the rotation. The derivatives $\frac{\partial C_L}{\partial r}$ $\frac{\partial C_N}{\partial p}$ of one of the lateral moments with respect to the angular speed about the other axis are the coefficients depending on the mutual effect of the rotation of one upon the other. The first of these derivatives characterizes the effect of a turn on the rolling moment, a phenomenon which we mentioned above. According to the convention we have chosen for the axes, the derivative $\frac{\partial C_L}{\partial r}$ is always negative. A knowledge of these values is necessary for the solution of the mathematical problem. As their determination by computation is only approximate and their determination by tunnel experiments is still a matter of investigation, there are few cases where the method has been applied to effectively constructed airplanes. It is nevertheless interesting to examine the type of solutions obtained. The general solution is of the same form as that obtained in the study of longitudinal stability. The displacement δv, δp, δr, and $\delta\varphi$ have the following values:

$$\left.\begin{aligned}
\delta v &= C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} + C_3 e^{\lambda_3 t} + C_4 e^{\lambda_4 t}\\
\delta p &= l_1 C_1 e^{\lambda_1 t} + l_2 C_2 e^{\lambda_2 t} + l_3 C_3 e^{\lambda_3 t} + l_4 C_4 e^{\lambda_4 t}\\
\delta r &= m_1 C_1 e^{\lambda_1 t} + m_2 C_2 e^{\lambda_2 t} + m_3 C_3 e^{\lambda_3 t} + m_4 C_4 e^{\lambda_4 t}\\
\delta\varphi &= n_1 C_1 e^{\lambda_1 t} + n_2 C_2 e^{\lambda_2 t} + n_3 C_3 e^{\lambda_3 t} + n_4 C_4 e^{\lambda_4 t}
\end{aligned}\right\} \quad (1)$$

the quantities λ being the roots of the characteristic equation

$$\lambda^4 + A_1 \lambda^3 + A_2 \lambda^2 + A_3 \lambda + A_4 = 0 \qquad (2)$$

These roots for lateral motion always take the following form: a pair of conjugate imaginary roots λ_1 and λ_2, defining an oscillatory motion, and two real roots λ_3 and λ_4, each defining an aperiodic motion. The general solution shows that each of these types of motion arises, following a law of motion derived from the sum of each of these three motions. The displacement $\delta\psi$ may be detrmined for each instance by integration with respect to δr dt. It is known that the displacements decrease with time and that the motion is consequently stable when the roots λ, are negative. For complex roots the real part should be negative. This occurs when each of the quantities

$$A_1, A_2, A_3, A_4 \quad \text{and} \quad R = A_2 - \frac{A_3}{A_1} - \frac{A_1 A_4}{A_3} > 0$$

(Routh's criterion).

Let us take as variables x and y the coefficients $\frac{\partial C_L}{\partial j} = x$, $\frac{\partial C_N}{\partial j} = y$. For the other characteristics we shall take values usually realized for small angles of attack. The expressions A_1, A_2, A_3, A_4, and R are functions of the variables x and y. Let us limit the region considered to values of x and y between the limits -0.02 and +0.10, the angles being expressed in degrees. It is clear that the equations $A_3 = 0$, $A_4 = 0$, and $R = 0$ determine lines that cross the region considered in the xy plane (fig. 6).

The quantities A_1 and A_2 are, on the contrary, always greater than 0 for the values of the variables x and y considered. The lines $A_1 = 0$ and $A_2 = 0$ do not cross this region of the plane. The quantity A_4 becomes negative above the line $A_4 = 0$. It is positive below the line. The quantities A_3 and R have positive values above, and negative values below, the lines $A_3 = 0$ and $R = 0$.

It is evident that there is a region between the lines $A_4 = 0$ and $R = 0$ corresponding to a state of stability. A complete computation shows us that the condition $A_4 > 0$ leads to the equation

$$\frac{\partial C_L}{\partial r} \frac{\partial C_N}{\partial j} - \frac{\partial C_L}{\partial j} \frac{\partial C_N}{\partial r} > 0 \tag{3}$$

The derivatives $\frac{\partial C_L}{\partial r}$ and $\frac{\partial C_N}{\partial r}$ being negative, this condition may be written:

$$\frac{\partial C_N}{\partial j} < \frac{\partial C_L}{\partial j} \frac{\frac{\partial C_N}{\partial r}}{\frac{\partial C_L}{\partial r}} \tag{4}$$

Let us consider a series of points P_1, P_2, ..., corresponding to airplanes having given values of x, y. We shall derive each time the corresponding solution of our equation in λ and the nature of the corresponding motion. If the coordinates x and y fix the point P_1 in the position shown on the figure, the airplane is dynamically unstable. It has spiral instability. One of the real roots - for example, the one we call λ_3 - is positive and the terms in $e^{\lambda_3 t}$ entering the general expression (1) show that these increase with time. The rate of increase depends on the size of λ; the term $e^{\lambda_3 t}$ doubles in value every $\frac{0.693}{\lambda_3}$ second.

In general, when the point P_1 is not too far removed from the limit of stability, λ_3 is small and the time required for any disturbance to double in value is large; for example, 20 seconds. The spiral instability in that case is not dangerous. For P_2, on the other hand, the airplane is dynamically stable; the root λ_3 has become negative. Condition (4) gives us a quantitative determination of the relation that should exist between the directional and rolling stability in order to avoid spiral instability.

The reasoning of the preceding paragraph has enabled us to foresee the existence of this relation.

In the neighborhood of points P_1 and P_2 the imaginary root determines a rapidly damped oscillation. When the coefficients for the airplane are such that the corresponding point is displaced toward P_3, the root λ_3 remains negative but the imaginary root takes on a disquieting character; namely, the real part of the root decreases, which indicates a badly damped oscillation. It is clear, in fact, that the airplanes possessing a lateral static stability that is too high compared to the directional stability, are likely to assume a continuous swinging motion. Let us imagine an initial disturbance causing the airplane to bank to the left, which causes the axis of the airplane to move to the right with respect to the trajectory. The coefficient $\frac{\partial C_L}{\partial J}$ being increased, the airplane will incline energetically toward the right while the tendency to turn to the left will be feeble since $\frac{\partial C_N}{\partial p}$ is small. This turning will not develop, as a secondary effect, any considerable rolling moment. From then on there will be nothing to oppose the rolling motion toward the right, and the airplane will lean over to this side. The lateral component of the weight will act to produce a skidding motion toward the right so that the same phenomena will occur in the reverse sense. The airplane will be subject to a yawing motion upon which a lateral swinging motion is superimposed. When the line $R = 0$ on the diagram is crossed in going from P_3 to P_4, the preceding oscillation does not tend to dampen out. On the contrary, the successive displacements will increase and the airplane will become unstable. For this condition the real part of the imaginary root is positive. The condition $R = 0$ determines the stability or instability of the oscillatory motion. Figure 6 has been calculated for the case of an airplane flying at small angles of attack. It is seen that the flight of an airplane is possible and that its motion may even be stable when its directional stability is negative provided this instability remains small.

In the foregoing we have not considered the real root λ_4. The latter, always negative, varies little with x and y and never gives rise to any difficulties. It always corresponds to a rapidly damped motion.

6. Large Angles of Incidence

Since an airplane is not always called upon to fly at small angles of attack, it is necessary to examine what happens for large angles of attack. After going over the preceding theory it is sufficient for us to point out that the conditions become steadily worse with increasing angles of attack. The damping factor for rolling $\frac{\partial C_L}{\partial p}$, may cease to become negative. When it becomes positive the well-known phenomenon of autorotation will appear. It no longer then satisfies the condition $R > 0$ and the oscillatory motion becomes more and more unstable. We may point out another source of trouble for large angles of attack: The directional coefficient of static stability of a given airplane always decreases when the angle of attack increases. It may at some instant become insufficient. We note these facts only to show that it is always proper to inquire whether the conditions of flight will be suitable for large angles of attack regardless of whether or not the airplane is provided with an automatic stabilizer.

7. Remarks

We see now how much more complicated the study of lateral motion is than that of longitudinal, and that the relative importance of the motions of the rudder and wings depends on the aerodynamic characteristics of the wing structure. We nevertheless believe that this introduction has been useful for seeing the problem clearly and for being able to give justification to certain assumptions adopted. To proceed logically it is necessary for our information first to determine what the degree of form stability is; that is, the value of the coefficients of static stability, which assures a most favorable trajectory for the airplane when it is flown without the intervention of the pilot. It is only when certain indispensable conditions have been satisfied by rational methods that it is necessary to investigate how the trajectory may be improved by a series of maneuvers which we entrust to the automatic stabilizer but which will inevitably be on the program of maneuvers imposed on pilots practicing blind flying.

M. R. Morane, discussing blind flying and automatic stabilization, wrote in L'Aeronautique, January 1934:

"It seems that blind flying should be perfected by automatic stabilization as far as the large transport airplanes are concerned which have to fly all the time, day and night. Moreover, the form stability which imposes a limit on the acceleration should be investigated before everything else."

We are happy to see that our theoretical conjectures agree with the ideas of a builder of such practical experience.

II. CLASSIFICATION OF AUTOMATIC LONGITUDINAL STABILIZERS

8. Constituent Parts

It is well known that every automatic stabilizer carries one or more disturbance detectors which controls the deflection of the corresponding controls.

Control is generally obtained by servomotors. The deflection obtained may be proportional to the magnitude of disturbance recorded - thanks to a device which stops the motion of the motor when the deflection has reached a proper value. The apparatus may be employed as an automatic pilot, allowing the airplane to climb, descend, or turn without exercising the usual direct action on the controls, provided it carries, between the disturbance detector and the servomotor, adjustable organs maneuverable in flight.

We shall examine separately the elements capable of affecting the longitudinal motion and those affecting the lateral motion. We shall only briefly consider longitudinal stabilizers, limiting ourselves to a completion of the study we made in 1932 of this type of apparatus by describing some new types, but shall make a more extended analysis of the lateral stabilizers.

9. Longitudinal Stability

The detectors of the disturbances of the variables concerned in the longitudinal motion are presented in table I. The disturbances detected are always utilized to adjust the elevator so that the manner of functioning of the various longitudinal stabilizers may be summed up as indicated in table II.

TABLE I. Detectors of Disturbances of the Variables Concerned in the Longitudinal Motion

Parameter	Variable	Nature of the Apparatus
1. Relative velocity	V or u	Anemometric plate or venturi
2. Angle of attack	$i = -\frac{w}{u}$	Vane placed in the wind layer
3. Inclination to the horizon	θ	Free gyroscope suspended from its center of gravity
4. Angular pitching velocity	q	Gyroscope producing a precession couple
5. Direction of apparent weight	$g \sin \varphi + \frac{du}{dt}$	Pendulum, level, or accelerometer along the x axis
6. Magnitude of apparent weight	$g \cos \varphi + \frac{dw}{dt}$	Accelerometer along the z axis
7. Lift	$iV^2 = uw$	Inclined plate constituting a wing element or a manometer indicating the difference in pressure between two suitable points above and below the wing
8. Rate of climb	$V \sin \theta$ or $\frac{da}{dt}$	Variometer (climb indicator

TABLE II. Longitudinal Stabilizers

Manufacturer	Variable whose disturbance controls the elevator	Control used
Etévé 1914	V	Direct.
Budig 1912	V	Direct.
Etévé 1910	i	Direct.
Constantin	i	Direct.
S.T.Aé.	i	Electric.
Regnard	θ	--
Sperry 1929	θ	Mechanical with clutches controlled by electromagnets.
Sperry 1932	θ	Oil pressure.
Smith	θ	Compressed air.
Lucas Girard-ville 1910	q	Direct.
Moreau 1912	$(g \sin \theta + \frac{du}{dt})$	Direct.
Doutre 1911	$(g \sin \theta + \frac{du}{dt})$ and V	Compressed air.
Askania	$(g \sin \theta + \frac{du}{dt})$ and V	--
Mazade	$(g \sin \theta + \frac{du}{dt})$ and V	Compressed air.
S.E.C.A.T.	$(g \sin \theta + \frac{du}{dt})$ and V	Mechanical with clutches controlled by electromagnets.
Doutre 1918	$(g \cos \theta + \frac{dw}{dt})$ and V	Compressed air.
Boykow	$(g \cos \theta + \frac{dw}{dt})$ and V	--
Gianoli	$(g \cos \theta + \frac{dw}{dt})$ and iV^2	Aerodynamic servomotor.
Boykow 1928	V and q	--
Siemens	V and q	Oil pressure.
Marmonier	V and θ	--
Pollok-Brown	θ	Oil pressure.

10 Longitudinal Stabilizers

The stabilization programs that we have defined in a previous paper, still remain the same. The new apparatus which we shall consider utilizes the following as reference variables:

1) Speed and direction of apparent gravity.

2) Speed and angular speed.

3) Lift and acceleration.

4) Inclination in space.

The first three stabilizers belong to the class of those that make use of the oscillations of the trajectory to determine the stability in velocity. The apparatus of the fourth class, depending on the inclination in space, is not applicable to the investigation of constancy in velocity. Experience has not yet decided between these two programs.

Let us briefly examine the combinations that have been used in practice.

<u>1. Speed and direction of apparent weight</u>.- Stabilization methods depending on the apparent weight direction have been applied to several apparatuses which were described by the author in 1932. The principle utilized is sound since the same indicators are used as in instrument flying, namely, the level and the anemometer. We may add to the apparatus of this class the elevator control used in the S.E.C.A.T. stabilizer. Figure 7, drawn schematically, explains the principle in a simple way. A pendulum (1) moving freely about its axis (2) is provided at its upper part with a plate placed in the relative wind. The pendulum should be damped; for this purpose it is enclosed in a sealed casing filled with oil. A brush moves before two contacts placed on a sector. Depending on whether the brush comes before one or the other contact, an electric current actuates in one direction or the other the mechanism controlling the elevator. The sector is displaced about the same axis as the pendulum. This motion assures the proportionality between the displacements of the pendulum and those of the elevator. The elevator control derives its energy from a continuously running electric motor. This motor carries wheels turning in opposite

direction and at equal speeds. Electromagnets by contact with one or the other of these wheels move a friction wheel whose motion in turn controls the elevator. This mechanism is not shown in the diagram of figure 7. A different application of the same principle is shown in figure 8. The two detectors are not attached to the same axis. The pressure plate may be placed at a certain distance from the pendulum, transmitting its motion to an auxiliary lever (5) by the intermediary of a transmission. Pendulum 1 turning about axis 2 is always of one piece with the brush, but sector 3 carrying the contacts, turns freely about two axes; it is toothed and engages a pinion on the auxiliary lever. A second sector (4), connected with the elevator, is likewise toothed and turns about the axis (2); a second pinion on the auxiliary lever moves on this sector. The two pinions engage each other. The method of operation is easy to follow. A decrease in speed produces a displacement of the lever in the direction of the arrow. Sector 4 being motionless, the two wheels should turn in the direction indicated by the arrows and sector 3 will be displaced backward. The brush is then before the front contact and the result obtained is the same as if the brush were displaced toward the front before a fixed sector. Displacement of the elevator control causes sector 4, which carries the wheels, to be displaced. The lever (5) which supports the wheels being fixed, the motion of the wheels should move sector 3 forward, the brush touching the nonconducting part separating the two sections. The functioning of the apparatus is also easy to understand in the other cases.

2. Translational and angular velocity.- The Siemens company has adopted the method of Captain Boykow. They have built an airplane with automatic operation of the three controls. The part of the equipment actuating the elevator includes a speed indicator and a gyroscope. Although the publications of the company do not expressly indicate the principle utilized, it seems that the apparatus applies, under a new form, the same stabilizer principle of Boykow (L'Aeronautique, 1932, p. 251) already described, namely the combination of the indications of a speed indicator and of a gyroscope having two degrees of freedom and an imposed rotation q. Any decrease in the speed V, or any negative angular velocity q tends to make the airplane dive and conversely. As soon as the desired motion is exceeded, the angular speed of the airplane undergoing the motion will bring about the opposite deflection of the elevator. This combination should

produce speed stabilization without troublesome oscillations, because the gyroscope prevents exaggerated corrections, which depend on the speed alone, arrests the action of the elevator, and even holds the airplane in its course as soon as the desired impulse is given to the apparatus. The simplified scheme given below explains the functioning of the apparatus (fig. 9).

3. Lift and acceleration.- The stabilizer of Gianoli successfully uses a new combination - lift and acceleration. It has recently been described in L'Aeronautique. This combination detects the disturbances in the angle of attack and the speed variations not producing any vertical acceleration. Sudden disturbances, corresponding to a strong momentary acceleration, do not, however, have any effect on the stabilizer.

The theoretical diagrams previously published describe the development of a disturbance. They show that the vertical acceleration is of short duration, but that there always exists a large residual disturbance affecting the speed. The inventor obtains damping of the fluctuations by not maintaining an absolute connection between detector and control. As soon as the return movement overshoots the mark, a reversing relay produces an opposite deflection, so as to brake the return motion of the airplane and prevent the position of equilibrium from being passed. Although the disturbances detected are those of speed and angle of attack, the difficulties due to the use of these reference variables appear eliminated as far as the production of badly damped oscillations is concerned.

4. Inclination in space.- The gyroscopic apparatuses which maintain a fixed direction in space, produce a type of piloting which does not at all tend, in bad weather, to reduce the vertical accelerations. In spite of this difficulty certain gyroscopic stabilizers have come into practical use, such as the American apparatus of Sperry and the English apparatus of Smith. We shall describe these below in detail. They utilize the three controls and possess each two gyroscopes.

The Sperry comprises a gyroscope with vertical axis controlling the elevator and the ailerons, and a gyroscope with axis horizontal controlling the direction. The Smith has a gyroscope with axis approximately horizontal controlling the elevator and rudder, and a second gyroscope with axis horizontal controlling the ailerons. In each of these cases the stabilizer of the elevator is therefore combined with one of the lateral stabilizers. We may point out that there is still another English stabilizer the Pollok-Brown, which utilizes two separate gyroscopes, as those of Smith.

5. Remarks.- Before concluding this rapid review of longitudinal stabilizers, we shall say a word about the vertical velocity used as reference variable. The climb indicator has not yet been utilized, but its use has been advocated recently by M. G. Robert. It is known that the modifications of the trajectory are accompanied in the modern fine high-speed airplane by considerable changes in the vertical speeds. In instrument flying the pilot actually observes the climb indicator with more attention than the inclinometer. It therefore appears that the use of the climb indicator merits some study. The climb indicator does not decelerate the initial disturbance. It may be used where the function of the stabilizer is limited to that of an organ for the damping of the trajectory oscillations. At the beginning of each disturbance the airplane would act as if it were deprived of any stabilizer, the latter coming into action only when the trajectory is sensibly altered. In case of gain or loss of altitude due to ascending or descending currents, the climb indicator would act with sufficient energy as soon as the disturbance occurred.

The gyroscopic apparatus makes corrections for the disturbances that assail the airplane in agitated air. As it tends to oppose any natural movements of the airplane and utilizes a particularly sensitive detector, it produces, as is well known and established, extremely sudden reactions. The variometer (climb indicator), on the contrary, would behave like a phlegmatic pilot, only coming into action when the apparatus has considerably departed from its straight-line trajectory. It is, in short, possible to realize several kinds of automatic piloting, the gyroscopic and climb-indicating apparatus being two extremes, as it were. We see in this possibility one of the reasons for the interest in automatic stabilizers. When the problem to be solved shall have been stated more precisely, a great step will have been taken in the direction of stabilization.

III. CLASSIFICATION OF AUTOMATIC LATERAL STABILIZERS

11. Lateral Stability

The problem is treated in the same way, as far as lateral stability is concerned. The detectors of the disturbances utilized are presented in table III. In the same way as for the longitudinal stabilizers, the indications of several detectors are often combined by a mechanical arrangement before being transmitted to the servo-motor. These indications may be used to control either the rudder, the ailerons, or both.

TABLE III. Detectors of Disturbances of the Variables Concerned in Lateral Motion

Parameter	Variable	Nature of the Apparatus
1. Angle of sideslip	$j = \frac{v}{u}$	Vane with vertical axis.
2. Inclination of the OY axis to the horizon	φ	Free gyroscope suspended from its center of gravity
3. Azimuth	ψ	Free gyroscope, or magnetic compass, or earth inductor compass.
4. Angular velocity of rolling	p	Gyroscope producing a precession couple.
5. Angular velocity of yaw	r	Gyroscope, or difference in linear speed of two wing tips.
6. Direction of apparent gravity	$g \sin\varphi + \frac{dv}{dt} + Vr$	Pendulum in the ZOY plane or accelerometer along the OY axis.

Numerous combinations are possible. Table IV sums up the solutions employed by the principal lateral stabilizers that have been proposed or built.

TABLE IV. Lateral Stabilizers

Manufacturer	Control parameter		Method of control
	Rudder	Ailerons	
Constantin	--	j	Direct.
Gianoli 1933	--	j	Aerodynamic servomotor.
Gianoli 1935	--	$(g \sin\varphi + \frac{dv}{dt} + Vr)$*	Aerodynamic servomotor
Mazade-Aveline 1922	r and $(g \sin\varphi \cdot \frac{dv}{dt} + Vr)$	$(g \sin\varphi + \frac{dv}{dt} + Vr)$ and r	Compressed air.
	The effect of the first parameter in each case being preponderant		
Askania	ψ and r	-	Compressed air.
S.E.C.A.T.	ψ	$(g \sin\varphi + \frac{dv}{dt} + Vr$ and $j)$	By motor with electrically controlled clutches (both S.E.C.A.T. rows)
S.E.C.A.T.	ψ	$(g \sin\varphi + \frac{dv}{dt} + Vr)$ and r	
Sperry	ψ	φ	Oil pressure.
Pollok-Brown	ψ	φ	Oil pressure.
Smith	ψ	φ	Compressed air.
Siemens	ψ and r	$(g \sin\varphi + \frac{dv}{dt} + Vr)$ and r	Oil pressure.
Orain	--	--	Direct

*L'Aeronautique, November 1929.

12. Different Programs for Lateral Stability

An examination of the apparatuses that have been constructed shows that the inventors have proposed different solutions. We shall here attempt to classify them. We shall see that certain tendencies, which we shall characterize below, are revealed from an examination of the table. These tendencies are:

1) Utilization of the angle of sideslip j.

2) Utilization, for the directional control, of the azimuth ψ.

3) Utilization, for the aileron control, of the inclination to the horizon φ.

4) Utilization of a whole group of reference variables, the apparatus acting as a flight control.

We shall briefly describe each of these:

1) Utilization of the angle of sideslip.- We have shown that the use of a vane sensitive to the angle of attack, for controlling the elevator, has no other effect than increasing by an artificial means its coefficient of static stability. Similarly, a vane with vertical axis sensitive to the angle of sideslip and operating one of the two lateral controls, will increase the corresponding static stability. It may therefore be foreseen what the effect of a stabilizer sensitive to the angle of sideslip will be. This stabilizer will displace, on the diagram of figure 6, the "figurative point" of the airplane and the changes in characteristics, the improvements in the trajectory which may be obtained being of the same order as those that may be produced by proper apportionment of the two coefficients of directional and rolling stability.

2) Utilization of the azimuth ψ.- Since the airplane does not possess the sense of direction or azimuth, why not provide it with one by means of an automatic stabilizer? Such is the question which inevitably arises in the study of lateral dynamic stability. Duval has touched upon this problem in these columns* and had stressed the difficulty which pilots experience in maintaining the course by the compass.

*L'Aeronautique, November 1929.

We see that the use of the azimuth as a reference variable is of interest, but it is not sufficient to stabilize the airplane effectively. It has been necessary to supplement the utilization of the azimuth disturbances by the disturbances of one other parameter, at least.

The S.E.C.A.T. and Sperry stabilizers actuate the rudder upon disturbance of the course, but they also automatically control the ailerons under the action of another disturbance ($\delta\varphi$ for the Sperry, $g \sin \delta\varphi + \frac{dv}{dt} + Vr$ and r for the S.E.C.A.T.). Other apparatuses, notably those of Askania and Siemens, combine the disturbance $\delta\varphi$ and the results of the detection of the disturbance δr before controlling the movements of the rudder. We shall study in greater detail the functioning of the apparatus in a succeeding section.

3) Utilization of the lateral inclination φ.- The use of the lateral inclination as a reference proceeds from a simple idea: to bring about automatically the corrections which the pilot makes unconsciously when he flies in a straight line in clear weather. To maintain the lateral axis OY horizontal is logical only when it is attempted at the same time to keep the apparatus in a straight-line trajectory. This is why the control of the ailerons as a function of φ is always associated with the directional control as a function of ψ.

4) Utilization of the direction of the apparent gravity together with the angular velocity r.- The simultaneous use of these two references is the principle employed in the flight control as far as lateral motion is concerned. This method imitates, in fact, the maneuvers of the pilot who attentively follows the indications of his Badin instrument. Let

$$\varphi' = g \sin \varphi + \frac{dv}{dt} + Vr$$

When $\varphi' = 0$ the apparent direction of gravity lies in the plane of symmetry. If the airplane flies in a straight line, its OY axis is horizontal. When it turns, its transverse axis is inclined just the amount necessary for the turning to be correct.

The direct measurement of r, the rotational speed about the OZ axis, would remove any doubt and indicate which of these interpretations is correct. The first function of the stabilizer is to make the apparatus fly in a straight line; the second is to give the airplane the proper lateral inclination whenever any turning effect is imposed on it. The reference variables $g \sin \varphi + \frac{dv}{dt} + Vr$ and r have been utilized for this purpose in several ways. The solutions adopted for the Mazade-Aveline and Siemens will be examined in the following section.

13. Secondary Effects

Lateral controls exercise secondary aerodynamic effects of which it may be necessary to take account.

Let α be the deflection of the ailerons, positive when it tends to incline the apparatus to the right ($L > 0$); γ, the deflection of the rudder, positive when it tends to turn the airplane to the left ($N > 0$).

The deflection α of the ailerons, as a result of the difference in drag it produces, tends to make the airplane turn about the wing whose aileron is lowered. A deflection α therefore makes $N > 0$, which is an important effect.

The deflection γ of the rudder sometimes produces a couple L. Since the greatest portion of the rudder is generally above the OX axis a deflection to the left produces a small rolling couple to the right. The rolling couple produced by the direct action of the rudder, is small compared to the rolling couple produced indirectly by the rotation r due to the rudder. The direct and indirect rolling are generally in opposite sense.

The characteristics of the controls C_L and C_N as functions of α, C_L, and C_N as functions of γ, are measurable in the tunnel. The four derivatives are positive.

14. Utilization of the Sideslip Angle

The vane with vertical axis, controlling one of the two lateral controls, makes the rolling couple L or yawing couple N depend on the sideslip angle.

If the vane controls the rudder it will be connected so as to head the airplane into the wind and the coefficient of static stability of direction becomes:

$$\frac{\partial C_N}{\partial j} + \frac{\partial C_N}{\partial \gamma}\frac{d\gamma}{dj}$$

The tendency which the airplane possesses in virtue of its static stability to turn toward the side toward which it sideslips, is accentuated. If the vane controls the ailerons, it will cause the airplane to incline to the right when it sideslips to the left and the coefficient of rolling stability becomes:

$$\frac{\partial C_L}{\partial j} + \frac{\partial C_L}{\partial \alpha}\frac{d\alpha}{dj}$$

The connections existing between the vane and the movable member determine $\frac{d\alpha}{dj}$ or $\frac{d\gamma}{dj}$.

It is necessary, however, to take account of the secondary effects. By the first method, by which the vane is employed, the static stability of rolling becomes:

$$\frac{\partial C_L}{\partial j} + \frac{\partial C_L}{\partial \gamma}\frac{d\gamma}{dj}$$

which we have said would be small. By the second method, on the contrary, when the vane actuates the ailerons, the secondary effect of the latter may considerably increase the directional stability; we have

$$\frac{\partial C_N}{\partial j} + \frac{\partial C_N}{\partial \alpha}\frac{d\alpha}{dj}$$

The effect of a stabilizer sensitive to sideslip alone may therefore be foreseen from what we know of the effects of the combination of the two static stabilities.

L'Aéronautique, of August 1930, described the Constantin (reference 1) stabilizer and contains some practical information on this subject.

A type of airplane of Farman of very small inherent stability, whose ailerons were controlled by the vertical Constantin vane, made turns and deflected laterally by the action of the rudder bar alone. The lateral inclination was of the correct amount, perhaps better than that produced by a normal pilot, never being inferior to it.

When the airplane came out of a turn, a lag in recovery was observed, the airplane overshooting the distance before recovering. This is an inherent property of the stabilizer. The aileron maneuver producing recovery cannot, in fact, be produced except by a rotation of the vane, and the latter is only effective when there is an actual sideslip. The possibilities of stabilization by means of a vane are therefore limited. Any improvements in the trajectory that may be obtained are of the same order as those that may be produced by judiciously apportioning the two static stabilities. If one of these coefficients, for example $\frac{\partial C_L}{\partial j}$, is clearly too small, it would be easier on an airplane that is already constructed to add a vane controlling the ailerons, than to modify the construction of the airplane itself by increasing the dihedral. The vane will produce the same effect as an increase in $\frac{\partial C_L}{\partial j}$ but will not modify the fundamental characteristics of motion of the airplane.

Gianoli, who employed a vane in his first plans for lateral stabilization, has abandoned this method and now makes use of the apparent direction of gravity.

IV. AUTOMATIC STABILITY OF DIRECTION OR COURSE

15. Utilization of the Azimuth

We have shown that one of the great defects of the present-day airplane is the absence of directional stability. It is important to supply this missing sense to the airplane.

A second reason militates in favor of stability of direction. We have shown in our theoretical study that the permanent couples L and N, which result from the dissymmetry caused by the propeller, have been corrected or annulled. Such a result can only be obtained, however, for a single régimé. For any other régimé, the correction is no longer good and the airplane, abandoned to itself, will have a tendency to turn, not on account of instability but on account of dissymmetry. A good course stabilizer will correct this tendency at all regimes. For these reasons it is not surprising that so many constructors have attacked the problem of building apparatuses sensitive to any displacement of the longitudinal axis of the airplane with respect to a given direction.

The mathematical theory (reference 2) has already indicated how an airplane would behave whose rudder was deflected by an angle $\delta\gamma$, proportional at each instant to the displacement $\delta\psi$ of the OX axis of the airplane with respect to a fixed direction.

The sensitiveness to the disturbance $\delta\psi$ corresponds to the existence of a new derivative, namely, $\partial C_N/\partial\psi$, which is the coefficient of the stability of the direction or course and which should be negative for stability. When this derivative is different from zero, the characteristic equation of the fifth degree in λ no longer admits a zero root, and all the disturbances are represented by a sum of five potentials.

The equation in λ possesses two pairs of imaginary roots and one real root. When the roots are compared for the airplane stabilized in azimuth with those of the normal airplane having no course stability, it is found that the latter has an oscillatory motion with the second real root λ_4 that occurs in the motion of a normal airplane. This root λ_4 practically does not change in value. The root λ_3 corresponding to the aperiodic motion of spiral instability, on the contrary, has disappeared. The latter has combined with the new root to form the second oscillatory motion. Calculations show that the real part of this root is almost always negative. This new oscillatory motion will be stable although slightly damped and its period is rather long.* Theoretically, therefore, the utilization of the azimuth appears to be advantageous. Many constructors of stabilizers have wished to utilize the possibilities indicated by the theory. The disturbance detec-

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*Meredith has indicated the causes which in certain particular but exceptional cases render the oscillatory motion unstable. See Flight, July 26, 1934.

tors and servo-controls that have actually been built often employ very ingenious devices. It seems, however, that the utilization of the course stability does not constitute by itself a sufficient means to assure the lateral stability of the airplane.

When the airplane is inclined laterally, the stabilizer does not go into action immediately. It is first necessary that the airplane sideslip, tending, under the action of the directional stability, to head into the relative wind with respect to the new direction of the latter. It is only when the series of disturbances established has produced a change in azimuth that the stabilizer enters into action. The course stabilizer is incapable of assuring directly lateral stability; it can only oppose any changes in course which, in a normal airplane, constitute the residual deviation after any lateral disturbance whatever.

The role of the course stabilizer is well characterized if we refer to the procedure in blind flying. The pilot does not discover the disturbances in inclination $\delta\varphi$ by observing his compass. These disturbances are revealed by other instruments such as the gyroinclinometer or the artificial horizon, but when the pilot has intervened and righted his airplane he consults his compass each time to set the airplane back on its course.

The course stabilizer suppresses spiral instability, but, on the other hand, introduces oscillations because the airplane tends to overshoot its position of equilibrium. It possesses this tendency because, in the simple course stabilizer the rudder undergoes at each instant a deflection proportional to the displacement $\delta\psi$. The deflection $\delta\gamma$ is still applied when the airplane has returned to its position of equilibrium. It would be necessary, on the contrary, to suppress the deflection at the beginning of the return motion or even to reverse its sense, to prevent the position of equilibrium from being passed.

It is clear, in short, that the azimuth disturbance indicator may collaborate to produce correct piloting, but it alone is incapable of assuring this. We can understand why the azimuth reference variable utilized in many stabilizers has been supplemented by the detection of at least one other variable.

16. Methods of Utilizing the Azimuth Reference Variable

The various procedures that have been employed to give the airplane stability in its course are:

1) The utilization of the earth's magnetic field, either with aid of an earth inductor compass or with the aid of the ordinary magnetic compass.

2) The utilization of the fundamental property of free gyroscopes, namely, the invariability of the plane of rotation.

The apparatuses of the first group lead to a stabilization of the airplane axis with respect to a system of axes fixed on the earth, which is, in fact, the problem under consideration. We shall see that the use of such apparatuses involve a good deal of complication.

The apparatuses of the second group stabilize the axis of the airplane with respect to a system of axes fixed in absolute space. The completely free gyroscope is held in this system of axes and appears to be displaced slowly with respect to the earth as a result of the rotation of the latter. This displacement depends on the initial direction in which it is set rotating and on the latitude of the place where the test is made (fig. 10). The displacement of the axis of such a gyroscope amounts, in our latitudes, to about 5° or 6° per hour. Theoretically, the indication given by the gyroscopic apparatus is not the one desired. The disturbance which is to be revealed $\delta\psi$ is, in fact, that which is defined with respect to axes fixed to the earth. The slow velocity of displacement, however, of one system of axes with respect to the other makes the use of the gyroscope quite feasible. If it is a question of overcoming accidental disturbances $\delta\psi$ the phenomena are of short duration and the apparent displacement of the axis of reference with respect to the earth is insignificant. If it is a question of assuring navigation along a given course for many hours, the necessary corrections may be easily applied.

The gyroscope appears, on the other hand, to be more easily applied than the compass for adjusting the control of an airplane. We shall thus see, in spite of a theoretical defect inherent in the principle of the apparatus itself, the gyroscope used just as much if not more than the compass in stabilizers for course setting.

We shall now examine in greater detail the various solutions proposed.

17. Magnetic Course Stabilizers

1. The S.E.C.A.T. apparatus.- A detector of azimuth disturbances, based on the earth inductor compass, is the subject of a patent taken out by the S.E.C.A.T. We do not know whether the apparatus has actually been built or whether it functions properly. The apparatus shown in figure 11 controls the rudder as a function of $\delta\psi$ and is part of the unit, the entire equipment comprising the control of the governor described previously, and the control of the ailerons described below.

An armature (1), the commutator of which is connected to two brushes (2), turns in the earth's magnetic field. The difference in voltage between the brushes is zero when the plane of the brushes is parallel to the earth's magnetic field. The brushes (2) feed a movable bobbin (3) placed between the poles of an electromagnet (4), whose excitation coil is fed by a battery. Under the action of the springs (5) the bobbin (3) occupies a mean position. When a current flows in it, it is displaced in one direction or the other under the effect of the electromagnet (4). The direction is determined by the relative displacement of the brushes (2) with respect to the earth's field. The motion of the bobbin (3) determines the displacement of the lever (6) in front of the contacts (7) which actuate the rudder. It is clear that the functioning of the apparatus requires that the plane of the brushes coincide with the magnetic meridian when the airplane is oriented in its required course. The support of the brushes is therefore necessarily adjustable by the pilot, the position of the plane of the brushes with respect to the axis of the airplane being given on a graduated quadrant.

2. Details of the compass.- The construction of apparatus utilizing magnetic needles meets with many difficulties due to:

a) The weakness of the magnetic field.

b) The necessity of keeping the compass away from magnetic masses and of compensating their effect very carefully.

c) The difficulty of damping the compass without hurting its sensitivity.

d) The vertical component of the earth's magnetic field.

We shall examine each of these points in turn.

a) The weakness of the magnetic field has for many years rendered the construction of repeater compasses very difficult. It may therefore be seen that it is rather difficult to devise an amplifying apparatus for actuating a servomotor according to the compass indications. The difficulty has nevertheless been solved by two different methods which we shall consider farther on.

b) The second difficulty may, however, be overcome by a simple method. This consists in placing the compass in the after part of the airplane, so as to simplify the compensation and to profit by the power amplification apparatus which is necessary for controlling the servomotor.

c) The need for damping the compass makes it necessary for the movable equipments to move but slightly in their frames in the case of a sudden yaw of the airplane.

d) The vertical component of the magnetic field produces irregularities which make the compass appear as a capricious instrument to the unaccustomed pilot.

If the airplane during a turn inclines to the horizontal by an angle greater than the complement of the inclination of the magnetic field to the horizon, the magnetic needle should indicate, for certain positions of the airplane, a direction making an angle of 180° with the magnetic north. Even in turns made very slowly, almost level, the effect of the vertical component is felt.

We read in the Belgian military piloting manual the following: "In order to come out of a turn in blind flying and arrest the motion at a given direction, the turning should be stopped about 10° before arriving at the required course if this is included between NW and NE; it should be stopped 10° after arriving at the course if the latter is included between SE and SW; for the other two sectors the controls should be neutralized 4° or 5° before the required course."

Everything takes place as if it were necessary, in order for the magnetic needle to rest well on its supports, to increase slightly the weight on the south end. When the airplane turns, therefore, the centrifugal force exerts an additional force on the needle as shown in figure 12. It may be seen that when the airplane faces the north the centrifugal force makes the north end of the needle advance in the direction of the turn, whatever the sense of the latter. In order to stop the turn at a given direction, it is necessary, if the apparent indication of the compass is depended on, to stop the turn earlier. When the airplane is facing the south, the centrifugal force makes the south end of the needle come to meet the airplane; it is necessary to stop the turn later. For the east and west direction this effect is not noticed.

It is evident that the deviation depends on the angular speed of the airplane and on the radius of turn. The practical rule of the manual is given for rather low speeds, corresponding to a half division of the turn indicator.

We see, in short, that the compass is not an instrument giving in every case indications which may be depended on and moreover it must be used with great care.

<u>3. Insufficiency of the azimuth reference</u>.- The constructors who utilize the compass have combined it with another disturbance indicator, that of the angular velocity δr corresponding to the yaw. The apparatus, sensitive to the disturbances δr, is a gyroscope which develops a precession couple by means of which it controls the servomotor so as to counteract the rotation r. When the airplane is horizontal $r = \frac{d\psi}{dt}$. This stabilizer is, in fact, sensitive to the disturbances $\delta\psi$ and to their derivatives $\frac{d\delta\psi}{dt}$.

There exist several apparatuses of this type, those of Siemens, Askania, and Alkan. Descriptions of the first two have been published.

<u>4. The Siemens apparatus</u>.- The Siemens direction stabilizer is one element of the automatic-piloting apparatus made by this firm and acting on the three controls.

This stabilizer uses an electrolytic repeater compass.

The compass includes a float which rests on a conducting liquid. One electrode is fixed to the float, the other to the bowl. This electrolytic system is part of a Wheatstone bridge so that the displacements of the float, under the action of the magnetic needles, are transformed into variations of electric intensity. The system is so arranged that any deviation of the movable equipment to one side or the other of a given direction gives rise to a current. The latter, sent through a suitable coil, produces the angular displacement of a magnet. The stabilizer possesses, besides, a gyroscope with horizontal axis directed along OX. This gyroscope develops a couple about the OY axis when any displacement is imposed about the OZ axis. This couple is proportional to the angular speed δr of the displacement. Due to the action of a spring, the couple produces angular displacements proportional to δr. Figure 13 shows clearly how the angular displacements are combined and control the servomotor of the rudder. The arrangement for transmitting the indications of the compass from a distance are shown on the figure.

5. The Askania apparatus (figs. 14 and 15).- The Askania apparatus depends on the employment of a pneumatic repeater compass. Figure 14 shows the compass: the needle is of one piece with an eccentric disk placed in a low pressure chamber and which is displaced in front of two air inlets. Depending on its position, the disk more or less stops one or the other of the air inlets. On the other side of the disk are two tubes which lead to a differential manometer. It is evident that the indication of this manometer is a function of the position of the disk with respect to the tubes; that is, in the last analysis, of the position of the magnetic needles with respect to the bowl in which they are displaced. The displacements of the manometric membrane are communicated to an oscillating nozzle, which is a power amplifier. The nozzle, controlled by the manometer, is displaced before two openings which divide the current and communicate each with one face of the piston of the servomotor. A fluid under pressure escapes from this nozzle. Depending on the position of the nozzle with respect to the ports communicating with the cylinder, the piston is subjected to different pressures. Although the whole movement of the tip of the nozzle is very small (1.5 mm) and the ports are necessarily very small, this arrangement gives considerable amplification of the force exerted on the manometer membrane, without necessitating excessive pressures for

the fluid escaping from the nozzle. Air escaping at a pressure of 1 atmosphere is sufficient to assure the functioning of the servomotor controlling the direction. It is obvious that the construction of an amplifying apparatus should be very precise. It should be remarked that the nozzle is not controlled entirely by the manometer membrane but that it equally depends on a gyroscope for combining the indications. The gyroscope turns about the OY axis and rests on pivots placed along OX. A forced displacement about OZ produces a couple about OY. This couple produces a displacement about this axis which is transmitted to the nozzle as indicated on the figure. The gyroscope being free to move about the pivots OX, it will oppose (partly on account of the presence of the springs) the disturbances $\delta\varphi$ and will cause the rudder to deflect in case of rolling in such a direction as to restore the stability. The theory of the Askania apparatus is still more complicated. In fact, the constructor has recognized the necessity for adding a pendulum not shown on the figure and whose exact action is not known to us.

6. Remarks.- We find in the two preceding apparatuses two entirely different constructions based on the same principle. To detect the angular velocity r, it is necessary to carry along a gyroscope whose axis of rotation should be at right angles to OZ; it is seen that the two possible directions OX and OY, have been utilized. We may also remark that the Siemens gyroscopes are electric gyroscopes constituting the rotors of motors fed by a 333-cycle alternating current while the Askania gyroscopes have vanes and are driven by compressed air.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

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Constantin, Verdurand, and Volmerange: Remarques. L'Aéronautique, No. 135, p. 297.

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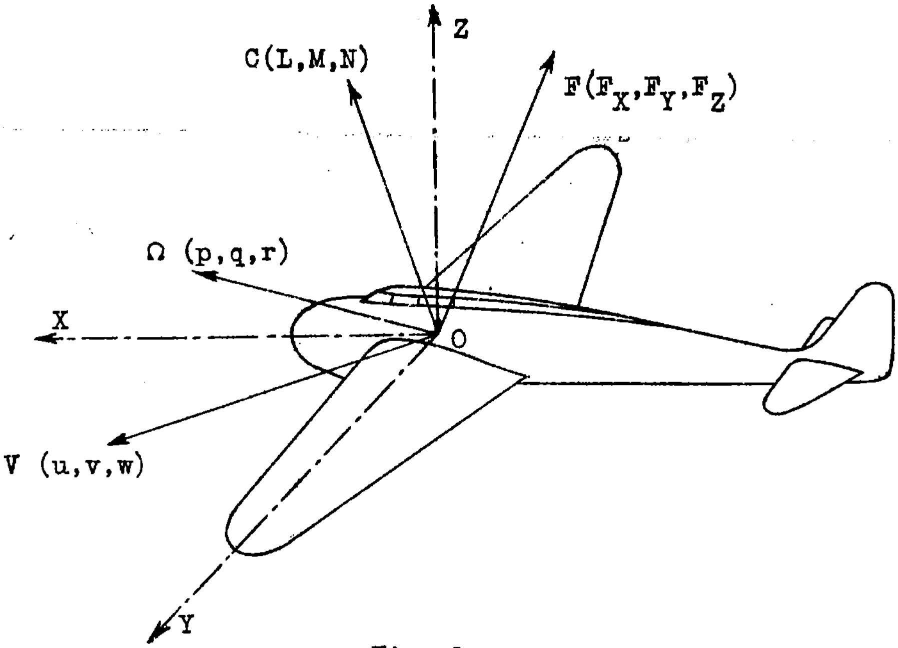


Fig. 1.

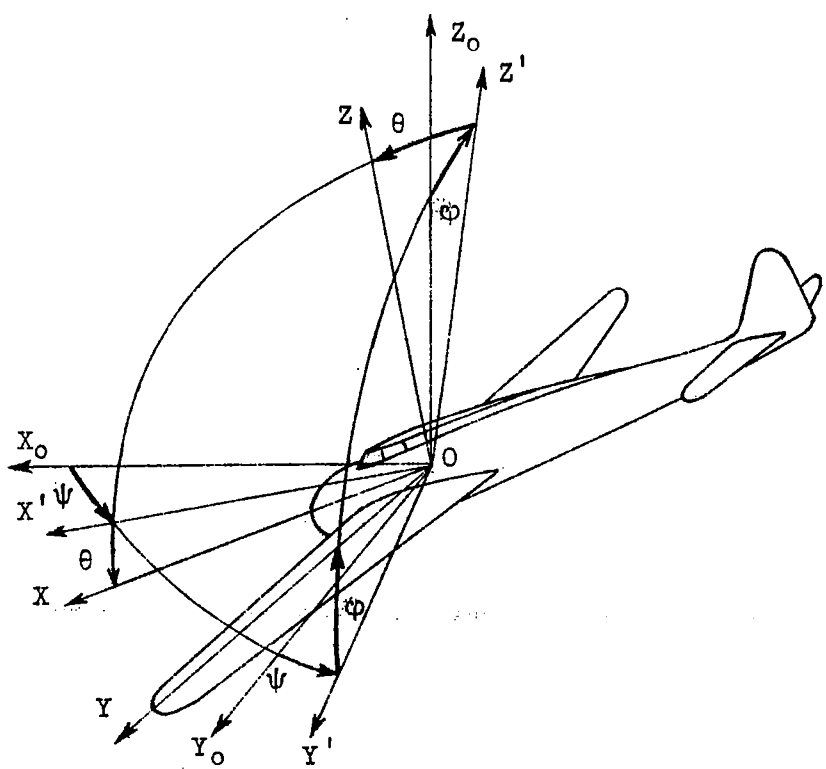


Fig. 2.

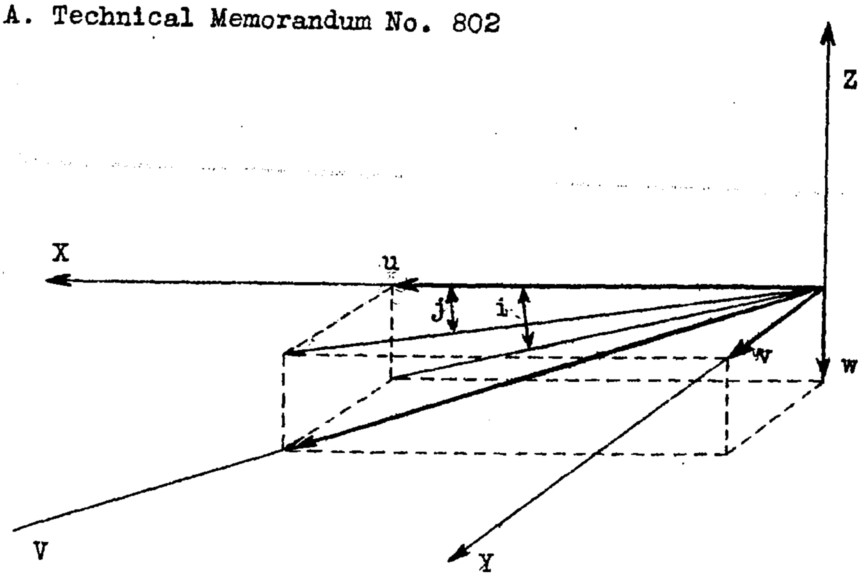


Fig. 3.

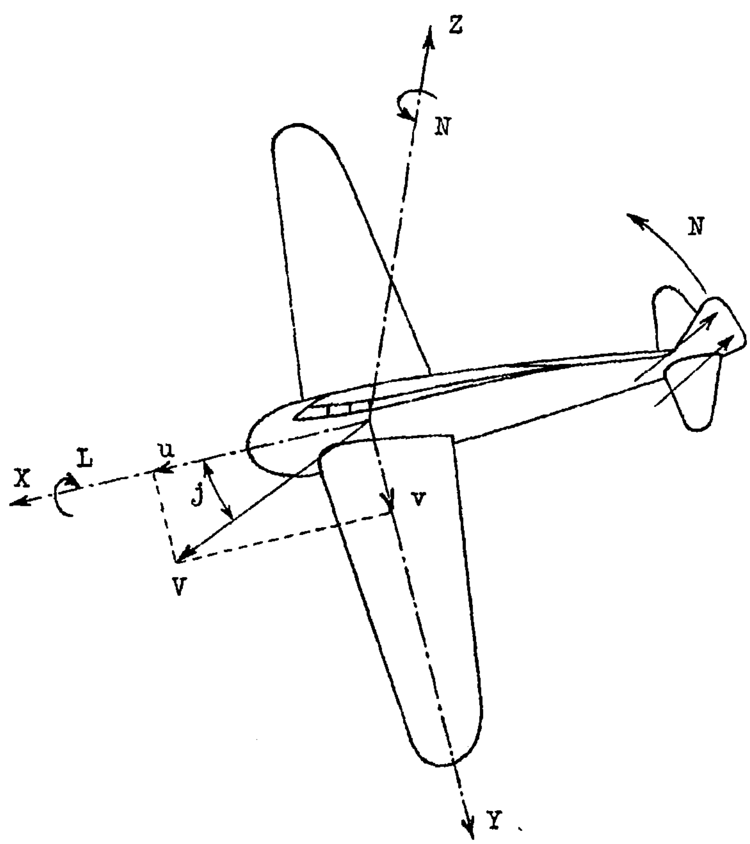


Fig. 4.

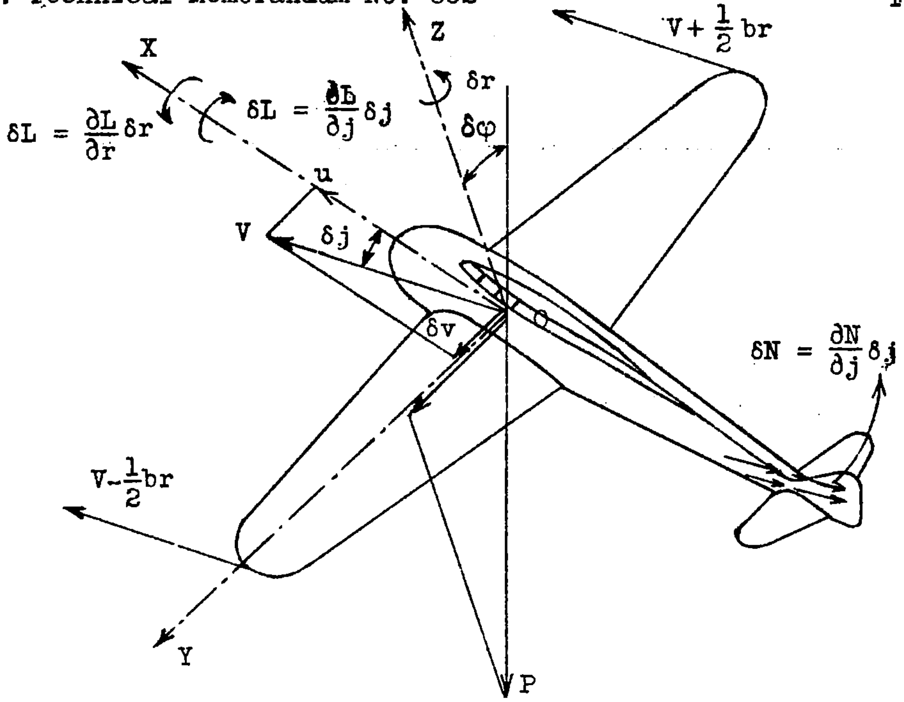

X
Z
δr
δφ
V + ½ br
δL = ∂L/∂r δr
δL = ∂L/∂j δj
u
V
δj
δv
o
δN = ∂N/∂j δj
V - ½ br
Y
P

Fig. 5.

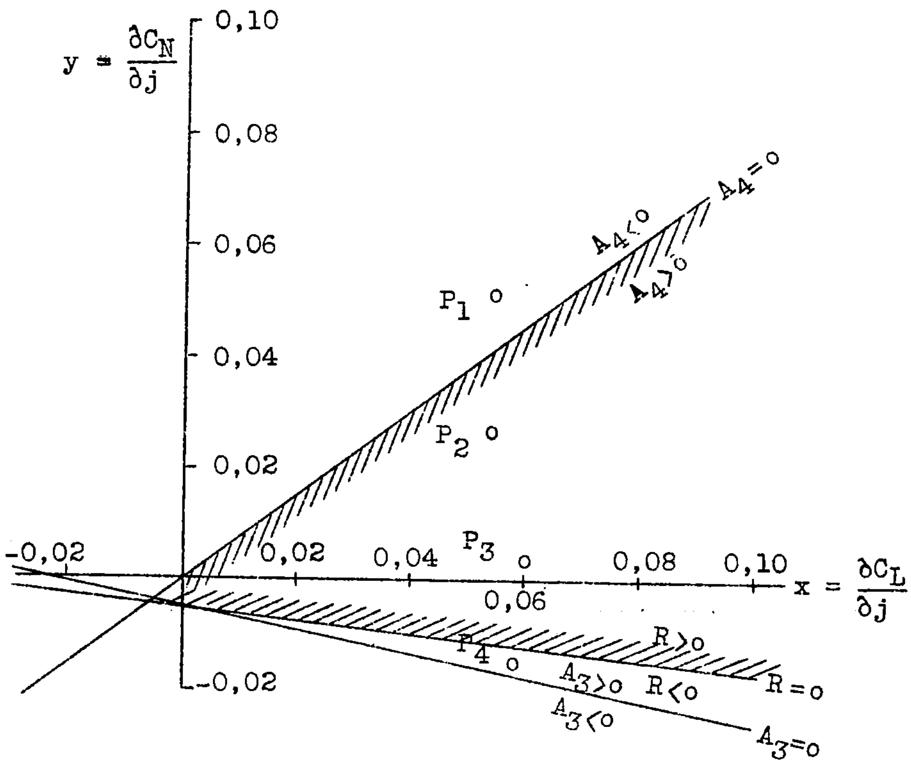
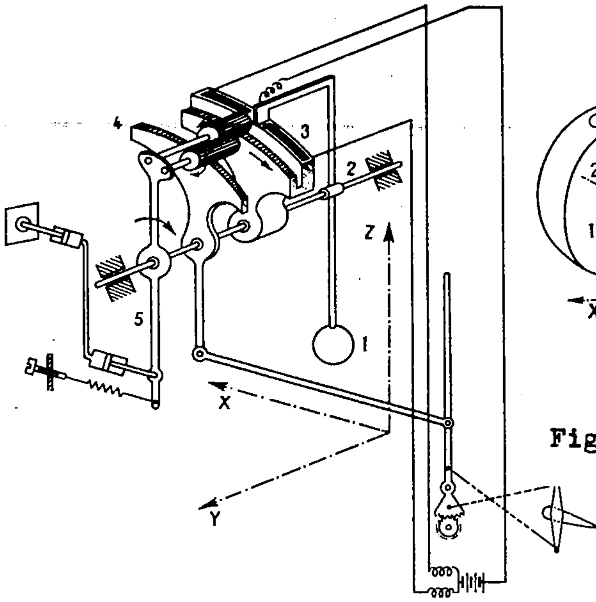

y = ∂C_N/∂j
0,10
0,08
0,06
0,04
0,02
-0,02
-0,02
0,02
0,04
0,06
0,08
0,10
x = ∂C_L/∂j
A4=o
A4<o
A4>o
P1 o
P2 o
P3 o
P4 o
R>o
R=o
A3>o
R<o
A3<o
A3=o

Fig. 6.



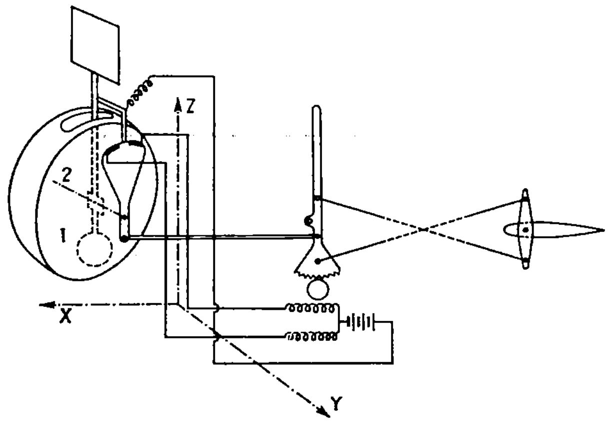
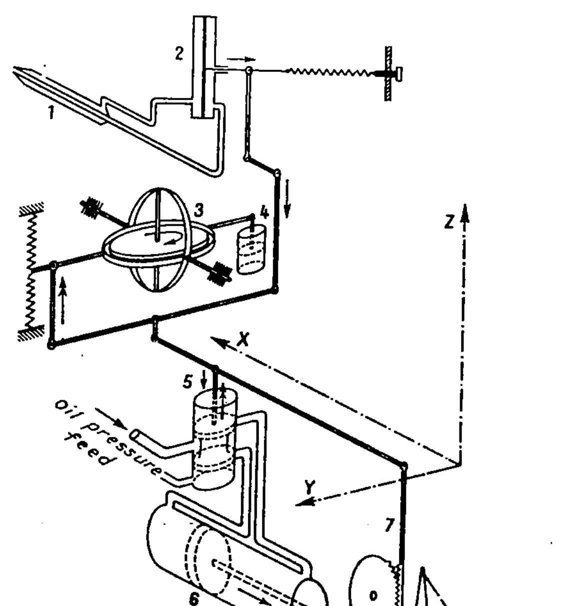


Figure 7.-Elevator control of the S.E.C.A.T. stabilizer.

Figure 8.-Variation of apparatus shown in figure 7 based on same principle.

Figure 9.-Sketch of Siemens-Boykow stabilizer. The simple arrows indicate the motions due to the decrease in speed, double arrows those due to angular speed.



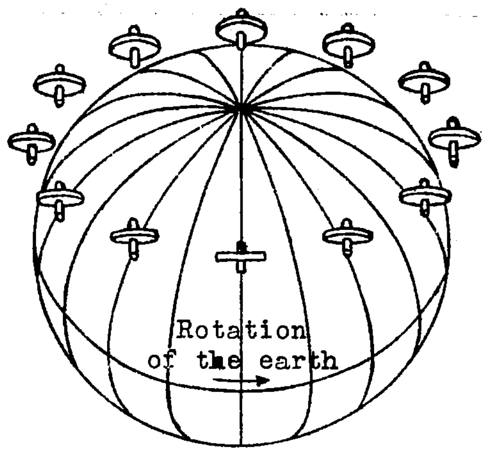


Figure 10. - Effect of the earth's rotation on a gyroscope.

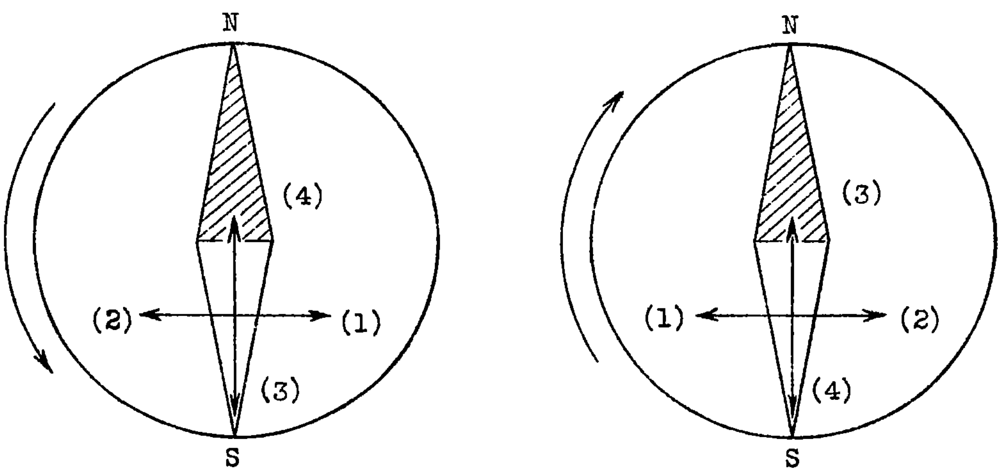


Figure 12. - Centrifugal effect on the magnetic needle. Outer arrow indicates direction of turning of the airplane. Centrifugal force exerted on south end of needle during a turn:
(1) When the airplane faces north.
(2) When the airplane faces south.
(3) When the airplane faces east.
(4) When the airplane faces west.

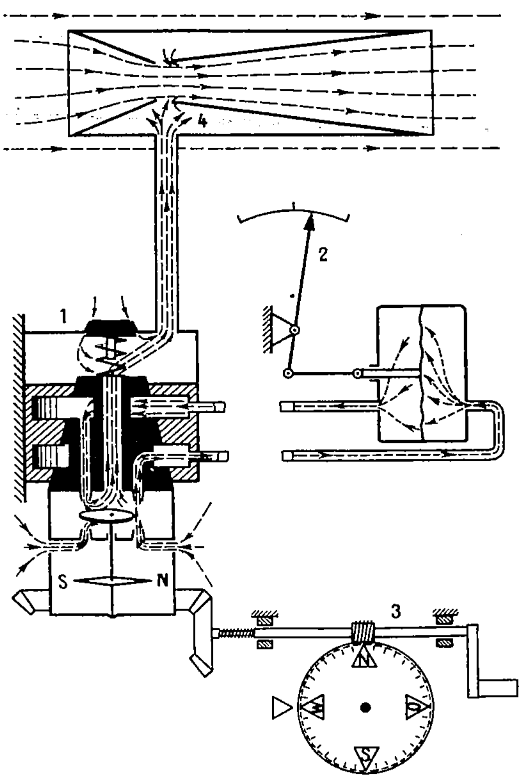


Figure 14.-Askania pneumatic repeater compass.
(1) Transmitting compass.
(2) Deviation amplifier.
(3) Predetermined course indicator.
(4) Venturi.

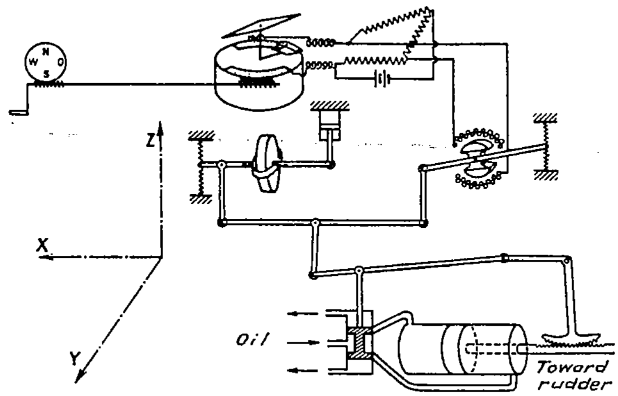
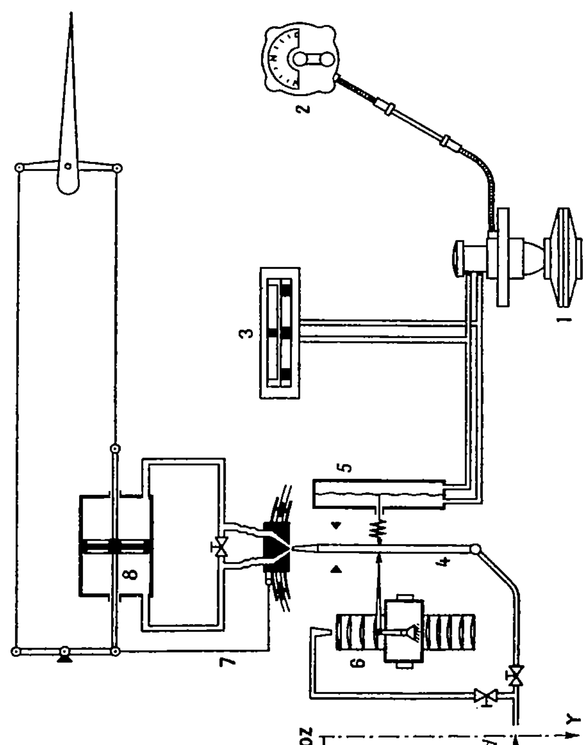


Figure 13.-Sketch of the Siemens direction stabilizer.



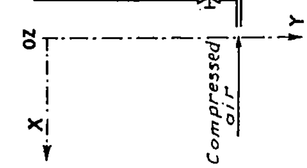


Figure 15.-

Askania course stabilizer.
(1) Transmitter compass.
(2) Repeater.
(3) Predetermined direction indicator.
(4) Nozzle.
(5) Capsule with membrane.
(6) Gyroscope.
(7) Connector.
(8) Servo-motor.

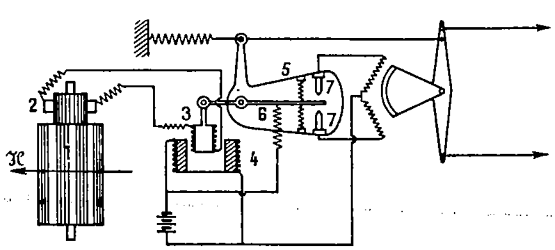


Figure 11.-S.E.C.A.T. stabilizer with earth inductor.