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TECHNICAL MEMORANDUMS

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No. 232

THE VERTICAL ACCELEROMETER,

A NEW INSTRUMENT FOR AIR NAVIGATION.

By Letterio Laboccetta.

From "Atti dell'Associazione Italiana di Aerotecnica,"
Vol. II, Nos. 3-4, 1922.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 232.

THE VERTICAL ACCELEROMETER,

A NEW INSTRUMENT FOR AIR NAVIGATION.*

By Letterio Laboccetta.

1. The pilot of a free balloon does not need to trouble about horizontal steering, since the direction of flight depends on the prevailing wind. He must, however, pay constant attention to vertical maneuvering.

In fact, careful consideration will show that a balloon is normally in a state of equilibrium, but constantly subject to varying forces which compel it to change its altitude. Only for a few moments can a balloon remain at the same altitude and even then its equilibrium is essentially unstable, since it may change at any instant.

If a balloon could start at zero velocity, that is, at the lowest practicable speed, then it might reach its navigation altitude without going beyond it, and, under ideal conditions, might remain in equilibrium at that altitude indefinitely. Actually the balloon starts at a speed which is often considerable and the altitude of equilibrium is passed at the first bound. Thus, much gas is lost and only by releasing ballast can the balloon be maintained at the altitude reached.

It is difficult, however, to calculate exactly the amount of

* From "Atti dell'Associazione Italiana di Aerotecnica," Vol.II, Nos. 3-4, 1922, pp. 106-115.

ballast to be released in order to compensate for the gas lost, or rather, to offset the variations of the total lifting force which, even with a partially inflated envelope cannot remain constant during the trip. It is therefore probable that either too much or too little ballast will be released. If too much, the balloon will again rise, since it is not generally advisable for the pilot to open the valve and let gas escape. Therefore, he does nothing and waits for the upward motion to cease. On the contrary, he must do something if the balloon begins to descend, either on account of gas lost in rising above the altitude of equilibrium or from the loss of lifting power owing to the cooling of the gas. In this case he must act promptly if he does not wish to come to earth.

Under such circumstances, it is a question of determining the exact amount of ballast to be released and of seeing that this amount is not exceeded, since excessive lightening of the balloon has two harmful consequences: It reduces the duration of the voyage and limits the zone of stable navigation, since the altitude of equilibrium rises each time ballast is thrown out.

2. What means does the pilot possess of knowing exactly the value of the vertical motive force and, consequently, the quantity of ballast to be released in order to keep the same altitude?

Although, as we see, the problem is essentially one of dynamics, the pilot has hitherto had at his disposal only instruments which might help him to solve it indirectly by deductions concerning the dynamical conditions of the balloon.

We may say that, thus far, he has only been able to estimate the vertical force by observing the atmospheric pressure. This method is doubly indirect, since he must pass from the pressure indicated by the barometer to the pressure at a certain altitude. For this purpose, he has the altimeter which gives immediately the correspondence between the two magnitudes to a sufficiently approximate degree for practical purposes. Then, knowing the altitude, he must deduce the motive force by observing the rapidity of the variations in altitude. For this purpose, he needs a barograph which traces the curve of pressure or altitude in function of the time. This second deduction could not be made immediately and it might well happen that circumstances would not allow the pilot time for it.

As a matter of fact, since the balloon is moving in a resisting medium, if the motive force remain constant, the descending speed will gradually become uniform. The curve shown by the barograph will therefore tend to assume the form of a straight, inclined line, that is, it will tend toward a practically constant slope. At this point, we can deduce the value of the motive force from the inclination of the curve, provided we know the characteristics of the balloon.

The motive force might, however, be so great that the balloon would reach the ground before attaining normal speed and therefore, even though the speed were constant, the pilot must maneuver himself out of the difficulty without waiting too long. It often happens that the motive force varies gradually and consequently the time required to attain normal speed is greatly prolonged. In this case, if the pilot wishes to avoid a forced landing, he must maneuver at once, without waiting for the curve to straighten out.

Or he might wish to keep his altitude, because of contrary winds prevailing in a lower layer of the atmosphere. He would then need to check the descent at once and the barograph would be of very little help. The pilot might refer to the readings of the statoscope or some such instrument, but the statoscope only indicates a change of altitude, and not, directly, the magnitude of the force producing it.

3. If the balloon were a free body not immersed in a resisting fluid, the value F of the vertical resultant of the forces acting on it, at a vertical velocity v, could easily be found by determining the acceleration $\frac{dv}{dt}$ at the moment. Knowing the mass of the balloon, we would have

1) $$F_v = M \frac{dv}{dt}$$

But since the balloon is immersed in air having a resistance R_v which may be considered proportional to the square of the velocity, we have

2) $$R_v = k\, v^2$$

in which k is a constant depending on the shape and dimensions of the balloon and also on the density of the air at the altitude of flight. It follows therefore that a moment will arrive when (the other forces acting on the balloon being constant) there will be no further acceleration and the velocity will assume a constant value V, which is the normal velocity corresponding to the motive force. Under such conditions the resistance R of the medium is equal and opposite to the vertical resultant F of the motive forces and we have

3) $$F = R = k V^2$$

Until this normal velocity has been reached, the vertical resultant of the forces acting on the balloon is given by the difference

4) $$F - R_v = k V^2 - k v^2$$

and for the acceleration, therefore, we have

5) $$M \frac{dv}{dt} = k (V^2 - v^2)$$

But knowing only the value of the acceleration, we cannot always determine the value of the motive force, which is

6) $$F = k V^2 = M \frac{dv}{dt} + k v^2$$

Perhaps this is the reason why no one has thought of making a device capable of giving the value of the vertical acceleration of the balloon directly.

But, though the motive force cannot usually be calculated from the acceleration alone, there is a moment when this can be done, namely, when the balloon reaches its maximum altitude at the end of an upward movement and begins to descend for loss of gas, after being carried beyond the altitude of equilibrium by the force of inertia; also, when the balloon being momentarily in equilibrium, a decrease in the lifting force initiates a falling motion.

In both cases, the velocity is very small at the beginning of the descent, the air resistance is negligible and, since we can write $v = 0$, in formula 5, the value of the force will be given by the acceleration, if the mass of the balloon is known. There is a substantial difference, however, between the two cases.

The balloon which has gone beyond the zone of equilibrium and has lost hydrogen, can be steadied by releasing ballast corresponding to the amount of gas lost.

~~In the second case, the beginning of descent is the first man-~~ifestation of a loss of lifting power, a loss which goes on increasing for some time. At the beginning, however, its final value cannot be predicted and, in order to avoid attaining an appreciable falling speed, the pilot must release ballast to counterbalance each small increase in the rate of descent.

Similar phenomena are experienced at the end of a descent when the fall is checked by releasing too much ballast. At the instant of the upward rebound, the acceleration will indicate the total value of the acting force.

If, on the contrary, the gas begins to get heated, and the balloon rises, the initial acceleration alone does not give the total increase of lift, since the heating process is continuous. Nor does the acceleration give this value later, when the ascending velocity v, begins to be appreciable, for equation 5 shows that, in order to estimate the total power, we must take into account both the rate of acceleration and the velocity at the given moment. This is also the case when the balloon has already acquired an appreciable falling speed.

From the preceding considerations we make the following important deductions concerning vertical maneuvers:

1. Having only speed indicators, the value of the lost lifting force to be compensated by releasing ballast can be determined only when normal velocity is reached. This is not always easy and is often quite impossible.

2. Having only acceleration indicators, the value of the variation of the lifting force, if this force is still undiminished, can be determined at the inception of the corresponding motion, or compensation may be effected while the motion is developing, if the balloon can be kept at a negligible speed.

3. If the balloon has already attained appreciable speed, the value of the motive force (allowing for the resistance of the medium) can only be determined by means of instruments registering both speed and rate of acceleration..

We may therefore say that, in order to determine just how much ballast to release, the pilot must have instruments giving simultaneously both speed and rate of acceleration. In particular cases, either one of these instruments may suffice.

4. For the perfect execution of vertical maneuvers, we must therefore, have instruments for measuring speed and also for measuring acceleration.

Instruments of the first kind are sometimes found on balloons (for instance, anemometers, driven by the relative vertical wind due to the motion of the balloon). So far as I know, however, no instrument has yet been employed for indicating vertical acceleration. This cannot be because such instruments are of difficult and complicated construction, and because they are not easy to use. On the contrary, no instrument could be simpler, both in construction and functioning, than a "vertical accelerometer."

Accelerometers for measuring horizontal speed have long been known and applied to various purposes and a great variety of accelerometers are used for studying the effect of shock. Their principle is very simple, being based on the resistance due to inertia. A vertical accelerometer can be constructed on this same principle.

"If a body is suspended from a spring balance, the balance will indicate the weight of the body at rest. If, however, the body is raised by the balance, the spring will yield, owing to the resistance of the inertia of the body. If the motion is continued at uniform velocity, the spring will resume the state of tension it had when the body was at rest and will continue in that state, since the force of inertia only makes itself felt when the velocity is changing, whereas gravity acts continually on bodies whether they are moving or at rest. We thus see that the tension of the spring may serve to measure variations in the velocity of a body and the magnitude of the resistance exerted by the inertia of the body in opposition to the force raising it."

These lines are quoted from Poncelet's "Industrial Mechanics"* and prove the importance of the force of inertia. They give, in fact, a clear description of the construction and functioning of a vertical accelerometer, especially in the phrase underlined. Of course, the word "accelerometer" does not actually occur, nor is there any hint that the experiment might be turned to a practical purpose.

Nevertheless, I considered the passage of sufficient interest to quote, since it is the earliest exposition I have found of the principles underlying the construction of a vertical accelerometer operated by inertia.

5. From all this it would appear that, in order to have a vertical accelerometer, it would only be necessary to take an ordinary spring balance, hang a weight on it, mark zero opposite the position of the pointer when at rest, and graduate the scale from this point upward and downward so that the rate of acceleration of ascent or descent would be indicated.

In point of fact, this might suffice, but would hardly be practicable, because if only a spiral spring and a rectilinear scale were employed, the instrument would be either too clumsy or not sensitive enough. To prove this, we have only to remember that the spring lengthens or shortens in proportion to the variation of the weight it is bearing. Therefore, if it is desired to make the instrument sensitive to small accelerations, the scale would have to be made very long, in order to indicate serious disturbances of equilibrium also.

* I. V. Poncelet. "Mechanique Industrielle," p.42, par. 66. Published in 1839, by Leroux & Company, Liège.

For instance, if we had a balloon with a mass of 1000 kg, and wished to register disturbances of equilibrium up to 50 kg in either direction, we would graduate the scale in divisions of 100 grams, so as to have 1000 divisions in all. But it is evident that if a sensitivity of 100 grams may be required for small accelerations, this degree of sensitivity would not answer for variations extending to tens of kilograms. We see, therefore, that we must have an instrument of variable sensitivity, very great for registering small variations and decreasing gradually as the motive force increases.

I will here describe a type of instrument which I have invented to meet these requirements. In size and shape it is like an ordinary altimeter or aneroid barometer and gives satisfactory results in all ordinary cases. The principle on which it works is the following:

Fig. 1 shows a ring a, which rotates about a horizontal axis o, with respect to which it is perfectly balanced. If a weight p, is attached to the ring, this weight will naturally tend to fall to a point vertically below o, thus causing the ring to rotate. But, if the ring is attached to the axis by a spiral or helicoidal spring m, the weight p, may be made to remain on the horizontal line passing through o and the ring will rotate anti-clockwise through an angle α and will assume the position it would have were the weight p, removed.

Let r be the radius of the ring, m the mass of the weight p, g, the force of gravity, and k, a constant, depending on the dimensions and type of the spring and also on the material of which it is made. This constant will then equal the moments relative to the axis o of the weight on the spring and equilibrium will be expressed by

7) $$k\alpha = r\,m\,g$$

If the ring is now subjected to a vertical upward acceleration w, in the direction of the arrow z, the weight p will fall, stretching the spring (since the forces of inertia and gravity are acting together) and the weight, having described an angle θ will assume a position p', where we shall again have the equalization of the moments

8) $$k(\alpha + \theta) = r \cdot \cos\theta\, m(g + w)$$

In this equation we see that sensitivity decreases as θ increases, since as a matter of fact, w must be infinitely great in order to induce a rotation θ of 90° corresponding, that is, to $\cos\theta = o$. This shows that a part of the graduations of the lower quadrant will never be utilized.

If the acceleration has a downward, instead of an upward direction, and has, therefore, the negative value w, due only to gravity (except in the extraordinary case of descending vertical currents), its value cannot be greater than g, and then when $g - w = 0$, there will be no weight on the ring and, θ being also negative, we shall have $\alpha + \theta = o$. This shows that an upward rotation cannot exceed the angle α.

It is therefore advisable to make adjustments so as to give the angle α an approximate value of 90°. But even then only about half of the circumference can be utilized for the scale: the upper quadrant for negative accelerations and the lower quadrant for positive accelerations.

However, by adopting the device shown in Fig. 2, we can double the length of the scale, that is, we can extend it to the whole of the circumference without increasing the diameter of the ring. As shown in the figure, the two rings a' and a'' are equal and revolve respectively about horizontal axes o' and o'', Each has a weight attached to it, p' to the left of ring a' and p'' to the right of ring a'', the action of the weights being opposed by that of the springs m' and m'', which are also equal and similarly placed.

It is evident that, whether the vertical acceleration be upward or downward, the two rings will always rotate through equal angles but in opposite directions. If, therefore, we place the rings on the same axis and fix a pointer on the rim of one and a graduated scale on the rim of the other, the rotation of 180° of both rings in opposite directions will cause the pointer to pass over the whole 360° of the scale and thus utilize the whole of the circumference.

Figs. 3, 4 and 5, give the plans of an instrument thus devised. Fig. 3 gives a front elevation, and Figs. 4 and 5 show two cross sections with the diametrical planes passing through the axis, one vertical and the other horizontal.

As shown in these figures, two equal disks 1' and 1" are mounted upon and rotate about a common axis 2. To disk 1' is attached the weight 3', and to disk 1" the weight 3", the weights being equal and at equal distances from the center. A spiral spring 4 joins the two disks and is attached to them by pins 5' and 5" respectively.

Each disk has a toothed rim and is geared by a conical pinion 7 to the vertical axis placed at the bottom of the vertical diameter of the case 6. The pinion 7 forms an integral part of a conical roller 8 geared with another conical roller 9 which, in turn, forms an integral part of a cylindrical wheel 10. This wheel is geared with another wheel 11 of which the pointer 12 forms an integral part. The arrangement of the gears is such that the pointer 12 and the forward ring revolve in opposite directions.

By regulating the transmission ratio of the gears, we can make the useful angle of rotation of both disks in either direction, less than 90°, correspond to a pointer revolution of 180°. Therefore, if the scale is traced on the rim 13 of disk 1', when this disk revolves clockwise, indicating an upward acceleration, while the disk is covering 90°, the pointer will cover 180° in the opposite direction and we thus have a total of 270° for tracing the graduation of the upward or positive accelerations. The same process takes place in descending acceleration. The two scales are thus superposed over an arc of 180°, but this can cause no confusion since, for upward accelerations, the pointer is in the left half-quadrant and, for downward accelerations, in the right half-quadrant. Moreover, in order to avoid placing the numbers one on another, the graduations are traced, as shown in the figure, on either side of the median line of rim 13.

In this way, we have a scale covering a total range of 540°, so that with a ring of 12 cm diameter, we can have a scale about 55 cm long, the whole of which may be utilized. This length is sufficient for measuring all possible accelerations.

The above explanation is sufficient to prove that it is not difficult to obtain the correct value and direction of a momentary vertical acceleration of a balloon. In some cases this is enough for the determination of the vertical motive force. In order to solve the problem in the most common case, namely, when the balloon has already acquired an appreciable velocity, it is necessary, as we have seen, to know also its velocity at the time. This value can easily be determined and combined in various ways with the other values given by the accelerometer, but this must be reserved for a later paper. We have here only endeavored to show the possibility of determining the rate of acceleration and the advantage of having such an accelerometer in addition to our other aviation instruments.

Translated by Paris Office,
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for Aeronautics.

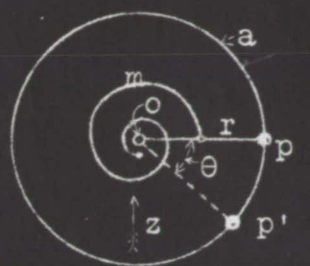
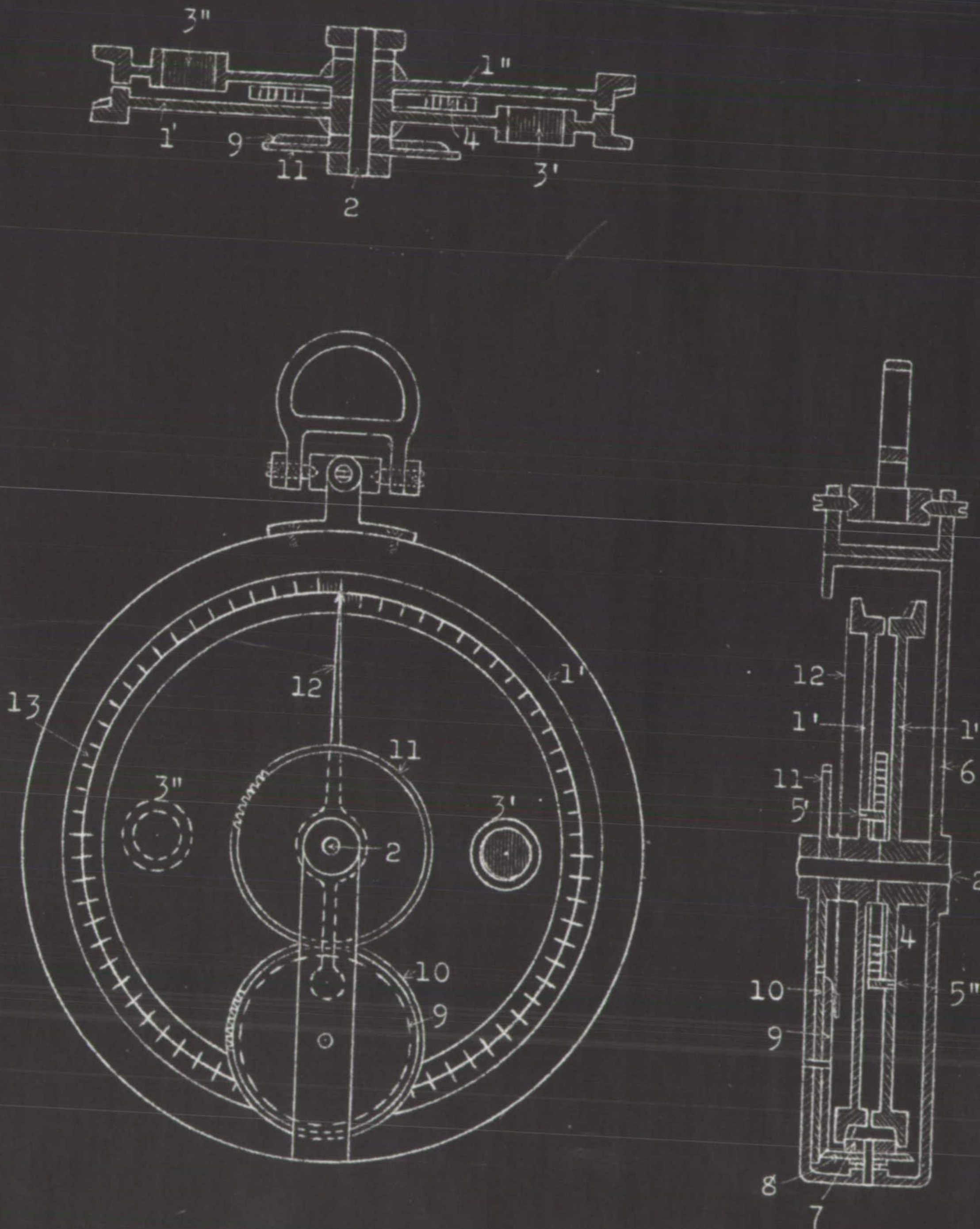


Fig.1

Fig.2

Figs. 3,4,5.



Figs. 3,4,5