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PART 2 : SECTION 1

CHAPTER 4

ARTIFICIAL HORIZONS

MK. 1 AND MK. 1B

Purpose

1. The artificial horizon provides the pilot with a direct continuous indication of aircraft attitude in the lateral and longitudinal planes, thereby replacing the natural horizon when this is invisible.

Implementation

2. A miniature aircraft, representing the rear view of the true aircraft, is rigidly mounted in the centre of the artificial horizon dial, and a movable bar behind the miniature aircraft represents the horizon. Provided that certain limits are not exceeded, the horizon bar remains horizontal regardless of the attitude of the aircraft, and moves up and down over the dial to indicate diving and climbing respectively. The miniature aircraft appears to bank in relation to the horizon bar when the real aircraft is banked. The attitude of the aircraft relative to the real horizon is thus shown exactly as it would be if the latter were visible.

3. A pointer moves over the scale at the lower edge of the instrument dial and denotes the angle between the horizon and the lateral axis of the aircraft, thus indicating the angle of bank in degrees.

4. The reading of the instrument is a direct interpretation and, since the image is fastened to

the case of the instrument and moves with the aircraft and because the horizon bar is gyro-stabilized to remain parallel to the true horizon, there is no lag in the indication of any change of attitude, provided that the instrument is not manifesting one of its temporary errors (which are described later in detail). Representative artificial horizon indications of various flight attitudes are depicted in Fig. 1.

Description

5. The movement of the artificial horizon is illustrated in Fig. 2. The gyro element consists of an air-driven *earth* gyro, the rotor of which turns about the vertical axis $Z-Z^1$ mounted in bearings in the gyro housing. The rotor revolves at approximately 12,000 r.p.m. in an anti-clockwise direction (viewed from above), and its housing is pivoted athwartships on the axis $Y-Y^1$ in a gimbal ring which is, in turn, mounted in the air-tight instrument case with its pivots in the fore-and-aft axis $X-X^1$. Indication of the vertical position of the gyro is brought, by the horizon bar arm, to the horizon bar on the face of the instrument. The horizon bar arm is pivoted on the gimbal ring and actuated by a guide pin which protrudes from the gyro-stabilized rotor housing. The horizon bar, *i.e.* the bar that the pilot sees across the face of the instrument, is therefore gyro-stabilized, and is arranged to be horizontal with reference to the earth's surface. When the aircraft moves

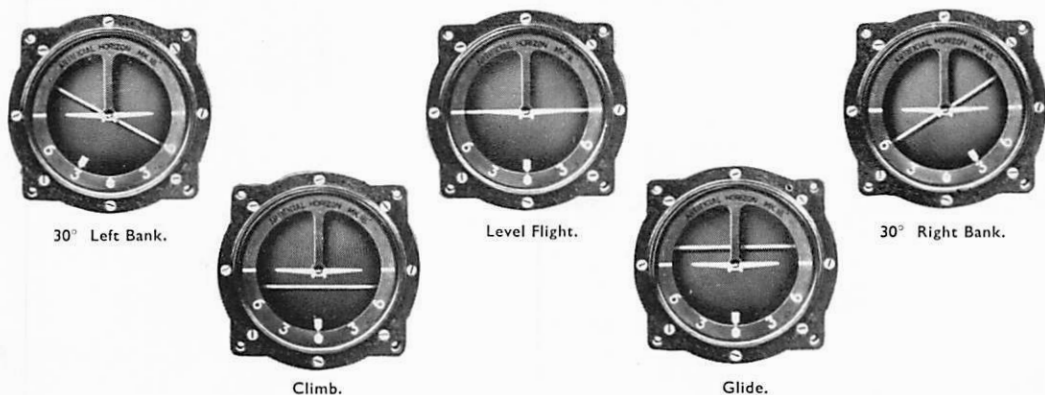


Fig. 1. The Mk. 1B Artificial Horizon, as the Pilot Sees It.

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into a diving or climbing attitude, the rotor case turns on the athwartships axis Y-Y' in relation to the outer gimbal ring, thus raising or lowering the horizon bar arm and horizon bar, thereby giving an immediate indication of diving or climbing to the pilot. Degrees of bank are indicated by a banking pointer attached to the gimbal ring, which reads on a scale on the face of the instrument.

6. When air is drawn out of the instrument case, by a suction pump or other medium of extraction, a partial vacuum of $3\frac{1}{2}$ inches Hg., with a tolerance of $\pm \frac{1}{8}$ inch Hg., is created *within the case*. Replacement air is drawn into the instrument through a filter mounted on the back cover, whence it flows directly into the bearing on the back cover (Fig 3 (14)) from which point it passes through holes in the pivot to a channel in the outer gimbal. Thereafter it passes through one of the inner gimbal pivots to the rotor case, where it divides to flow through channels to two driving jets, one of which is shown in Fig. 3 (4). Having discharged through one or other of the jets and provided motive force for the rotor through impingement on its serrated periphery, the air passes into the chamber (10) below the rotor case and flows out through the four exhaust ports (9) into the partially evacuated air-tight case of the instrument.

7. The exhaust ports, or discharge ports as they are sometimes called, are part of the *pendulous unit*, the function of which is to erect and maintain the rotor with its axis in a vertical position. The pendulous unit includes the chamber (10) beneath the rotor housing, the four discharge ports, and the pendulous vanes. The ports are located in the fore, aft, port, and starboard walls of the chamber, and suspended from a pivot point above each of them is a pendulous vane (7). The four vanes hang vertically under the influence of gravity, each giving half coverage to one of the four ports when the rotor axis is vertical.

8. If the rotor axis departs from the vertical, *i.e.* if the rotor departs from its horizontal position, as in Fig. 4, the chamber of the pendulous unit will move with the gyro, but the pendulous vanes will remain vertical. They are so constructed that as the rotor departs from the horizontal, one port opens progressively, while the opposite port closes progressively. When this occurs, neither the air jets from the opposing exhaust ports nor their jet reactions remain in equilibrium, and the differential reaction to the increased jet from the open port precesses the gyro back to its correct position. Erection in this manner occurs in both the rolling and pitching planes, and the combined effect of the four

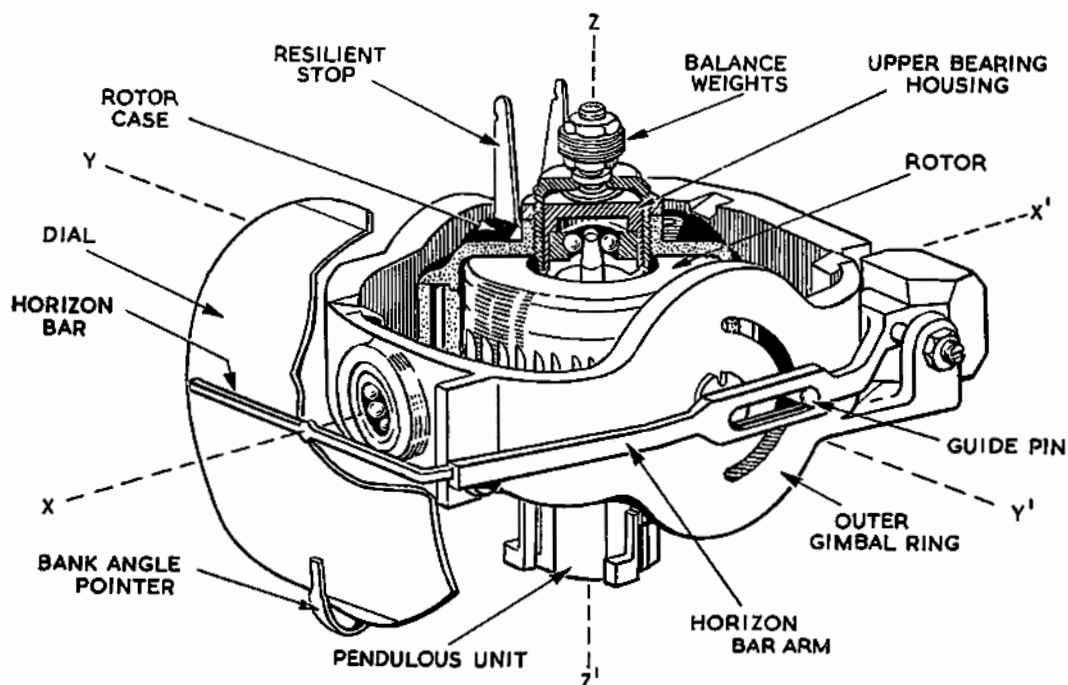


Fig. 2. Principal Parts of the Mk. 1B Artificial Horizon.

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ports and their vanes is to maintain horizontal stability within the operating limits. Since the gyro precesses slowly owing to its rigidity, any precessional forces due to the swinging of the vanes in rough air cancel out before they have time to displace the gyro.

9. It should be noted that although higher vacuum readings than $3\frac{1}{2}$ inches Hg. are specified in the Pilot's Notes for many aircraft, a proportion of the higher vacuum in those cases is lost through friction in lengthy suction system pipelines, and the partial vacuum remaining *within the instrument case* will be as stated previously, *i.e.* $3\frac{1}{2}$ inches Hg., with a tolerance of $\pm \frac{1}{8}$ inch Hg.

Errors

10. Mk. 1 and Mk. 1B artificial horizons are subject to acceleration, deceleration, and turning

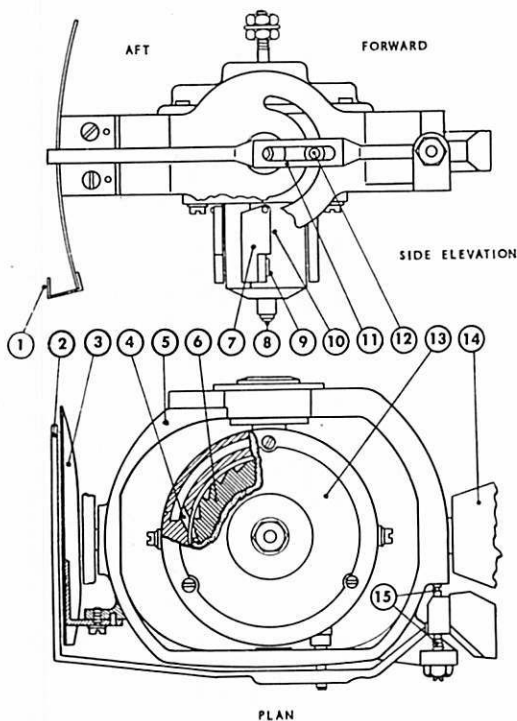


Fig. 3. Mechanism of the Mk. I Artificial Horizon.

- | | |
|----------------------|------------------------|
| 1 Banking pointer. | 8 Rubber-covered stud. |
| 2 Horizon bar. | 9 Discharge port. |
| 3 Background plate. | 10 Chamber. |
| 4 Driving jet. | 11 Horizontal bar arm. |
| 5 Outer gimbal ring. | 12 Guide pin. |
| 6 Rotor. | 13 Rotor case. |
| 7 Pendulous vane. | 14 Bearing. |
| | 15 Pivots. |

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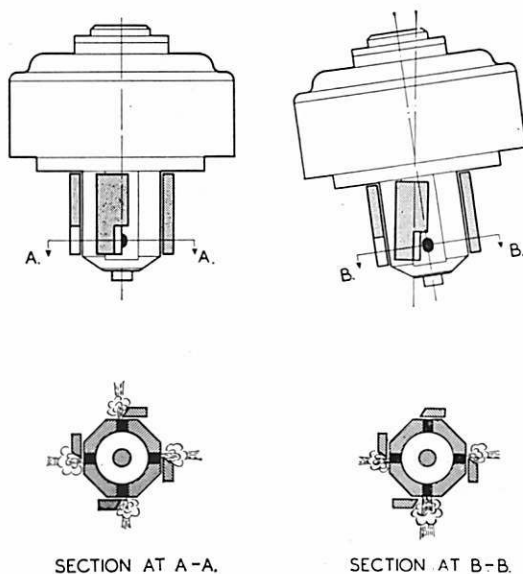


Fig. 4. Operation of the Pendulous Unit.

errors, and all pilots should be aware of the causes and effects of these errors.

Acceleration Error

11. Acceleration error occurs when the artificial horizon is subjected to acceleration of the aircraft in the fore-and-aft plane, and the effect is particularly noticeable during take-off.

12. In order to ensure rapid initial erection, the rotor assembly of the artificial horizon is constructed slightly bottom-heavy. When acceleration occurs, the base of the rotor assembly tends to lag behind owing to inertia, *i.e.* it tends to swing towards the pilot exactly as it would if a force were applied from the front of the aircraft towards the base of the pendulous unit. Owing to the 90° rule, however, the base of the pendulous unit in fact moves towards the starboard side of the aircraft. This movement causes a slight turning of the gimbal ring, and with it of the horizon bar, about the axis X-X¹ (Fig. 2). The direction of rotation of the horizon bar in this instance is anti-clockwise as seen by the pilot, *i.e.* the effect is an indication to the pilot of an apparent slight bank to starboard.

13. The initial cause, acceleration, also results in a rearward movement of the port and starboard pendulous vanes, owing to their inertia. Consequently, the starboard exhaust port dis-

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charges a larger jet of air than normally, while the diametrically opposed port discharges less. The differential jet reaction thus caused tends to push the base of the pendulous unit from starboard to port but, owing to the 90° rule, the actual movement of the base of the pendulous unit is towards the pilot. This impels the guide pin and horizon bar arm to move the horizon bar downward, thereby indicating an *apparent climb* to the pilot.

14. Thus the overall effect of acceleration on this instrument is the indication of a slight bank to starboard, and a climb. During the initial climb immediately after take-off it is therefore advisable to use the slip needle for reliable indications of lateral level, the airspeed indicator as the master pitch reference on piston-engined aircraft, and the rate of climb and descent indicator as the master pitch reference on jet-engined aircraft.

15. It is not possible to specify a definite time interval after which the pilot may assume that acceleration errors have ceased to exist, because the extent of the error depends on the magnitude and duration of the acceleration to which the

artificial horizon is subjected; both of which factors vary from one type of aircraft to another. It is known, however, that acceleration error no longer exists after twice the duration of acceleration; i.e. if when a particular aircraft takes off it accelerates for, say, 45 seconds before settling into a steady climb, then the acceleration errors will disappear after a further 45 seconds.

Deceleration Error

16. Exactly the opposite errors occur during deceleration. The base of the pendulous unit tends to swing forward owing to inertia, but the tendency is precessed through 90° and the actual movement of the base of the pendulous unit is from starboard to port and results in a false indication of a slight bank to port. The athwartships pendulous vanes swing forward owing to their inertia during deceleration, causing a differential jet reaction that tends to move the base of the pendulous unit from port to starboard but which, owing to the 90° rule, actually moves it away from the pilot, thereby indicating an apparent dive. The general effect of deceleration on this instrument is thus the indication of an apparent bank to port and an apparent dive.

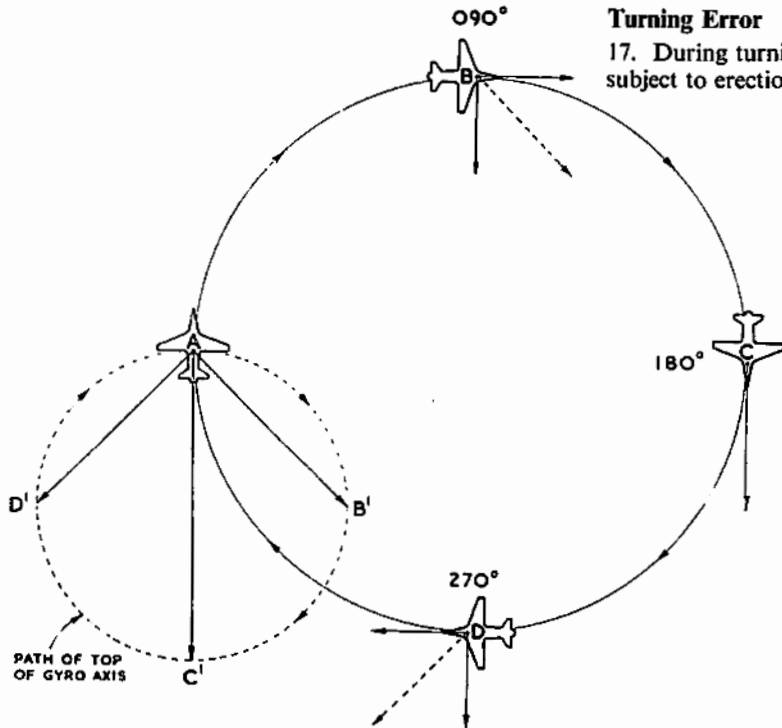


Fig. 5. Analysis of Erection Error, Uncompensated.

Turning Error

17. During turning, artificial horizons are subject to erection and pendulosity errors.

Erection Errors

18. Erection errors occur during turns as a result of displacement of the pendulous vanes by centrifugal force, and the consequent departure from the true vertical of the rotor axis.

19. In Fig. 5 the aircraft at point A is about to turn from a northerly heading through 360° to starboard. At the start of the turn the rotor axis is vertical. As the turn is entered, centrifugal force causes the fore-and-aft pendulous vanes to swing outward, reducing the jet and

jet reaction at the forward exhaust port and increasing the jet and jet reaction at the other port. The resultant tendency of the base of the rotor assembly to swing away from the pilot is precessed through 90° in the direction of rotation, and the base of the rotor assembly moves to port. This movement causes a slight turning of the gimbal ring and with it the horizon bar about the axis X-X¹ (Fig. 2). The direction of rotation of the horizon bar in this instance is clockwise as seen by the pilot. Thus if the true angle of bank is, say, 45° , the horizon bar movement causes a smaller angle of bank to be indicated by the instrument.

20. Since the bottom of the rotor assembly moves to port as soon as centrifugal force manifests itself, the top of the rotor axis moves to starboard, and it has been shown that this causes the artificial horizon to indicate an under-reading of bank.

21. If the behaviour during a 360° turn of a free gyro (one disembodied from its gimbals) is now considered, a plot can be made of the path of the top of the gyro axis in relation to the turn. As the centrifugal force experienced by the gyro axis during the turn is constant and

at right angles to the instantaneous heading, it follows that if the aircraft heading changes at a constant rate from 000° to 360° the top of the gyro axis itself describes a circle which is 90° in advance of the aircraft heading, as is indicated by the smaller, dotted circle in Fig. 5.

22. At point A, the point at which the turn is to be started, the gyro axis is vertical, and any chord of the smaller, dotted circle from point A indicates the tilt of the gyro axis top in relation to the true vertical. Thus the chord A-B¹ represents the direction of tilt after a 90° turn to starboard. If this tilt is now related to the earth gyro in its gimbals within the aircraft at point B, it is seen that the tilt can be resolved into two components, one forward and the other to starboard, giving erroneous indications of a climb and an under-reading in bank. Similarly, the chord A-C¹ indicates the direction of tilt after a 180° turn, when the tilt is at its maximum and is resolved at C into a forward tilt of the gyro axis in relation to the aircraft, giving a false indication of climbing. At point D the components of the tilt error represented by the chord A-D¹ are shown, their resultant being forward and to port, giving an erroneous indication of climb and an over-reading of bank. When the aircraft returns to point A the gyro axis tilt is zero.

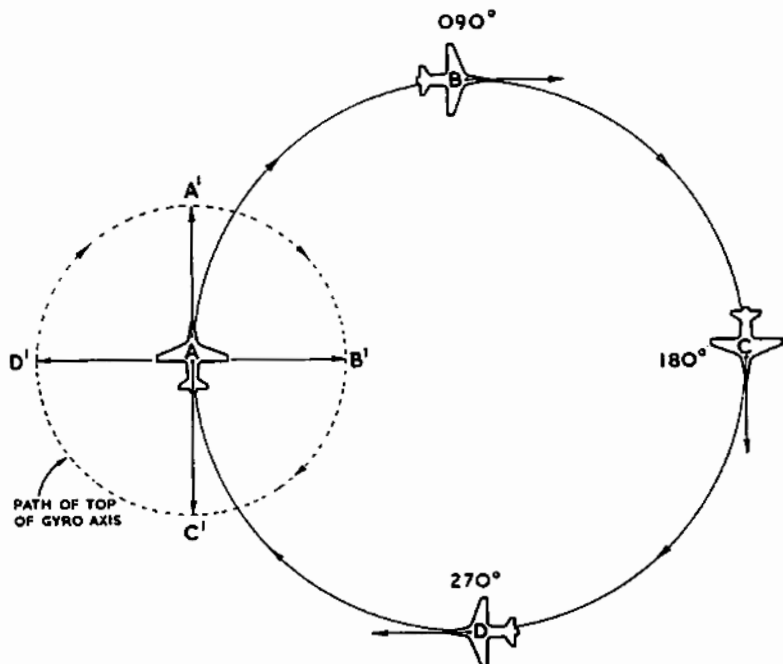


Fig. 6. Analysis of Compensated Erection Error.

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Compensation for Erection Errors

23. It has been shown that during a 360° turn to starboard at a constant rate the top of the rotor axis departs from the vertical, describes a circle in a clockwise direction, thereby causing *variable* turn errors, and returns to the original vertical position after 360° of turn. A brief consideration reveals that if it could be arranged for the top of the axis to describe a circle about *itself* during the turn, there would no longer be a variety of turn errors, but a single constant error which might be eliminated by a single constructional modification. In the Mk. 1B artificial horizon these qualities are in fact obtained by counter-balancing the athwartships pendulous vanes, so as to impart to the rotor axis top a constant forward tilt from the true vertical of $2\frac{1}{2}^\circ$ during level flight.

24. The effect of this is shown in Fig. 6, where point A represents the end of the true vertical through the centre of the rotor, and A-A¹ represents the direction of the forward tilt. It is now seen that during a turn to starboard the top of the axis describes a circle about point A at the same rate as the aircraft changes heading. Thus the amount of tilt and its direction in relation to the aircraft during the turn is constant.

Therefore there would be a constant erroneous indication of an apparent climb but for the fact that the horizon bar setting is modified in such a manner that, during level flight, when the rotor axis top is in fact tilted $2\frac{1}{2}^\circ$ forward, the artificial horizon indicates level flight. The extent of this forward tilt is based on a standard Rate One turn of 3° per second at 174 knots (200 m.p.h.).

Pendulosity Errors

25. Pendulosity errors occur during turns as a result of displacement of the rotor assembly, initiated by centrifugal force, and the consequent departure from the true vertical of the rotor axis.

26. In Fig. 7 the aircraft at point A is about to turn from a northerly heading through 360° to starboard. At the start of the turn the rotor axis is vertical. As the turn is entered, centrifugal force acts on the rotor assembly, which is bottom-heavy, and tends to swing its base to port. This tendency is precessed through 90° , and the base of the rotor assembly moves towards the pilot; *i.e.* the top of the rotor axis moves away from the pilot and the instrument indicates an apparent climb.

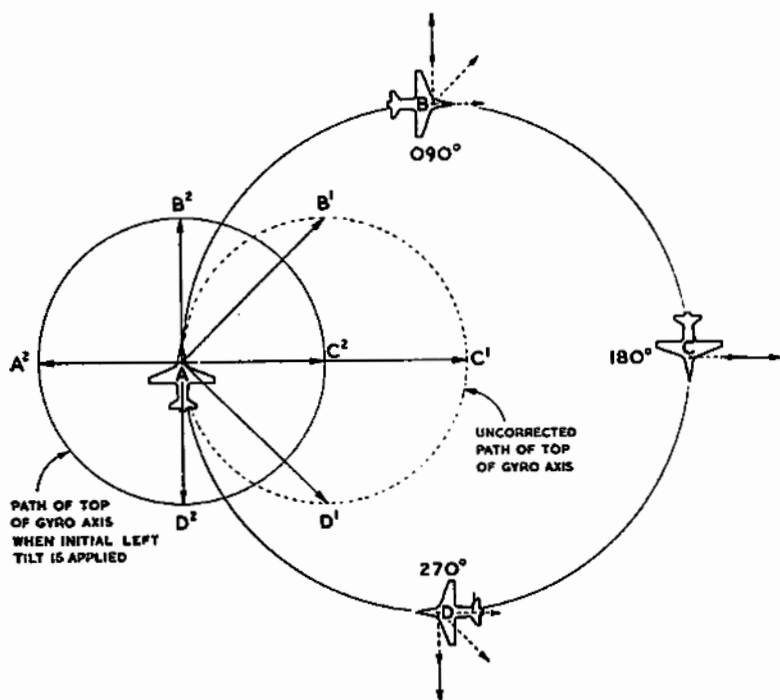


Fig. 7. Analysis of Pendulosity Error.

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27. The locus of the gyro axis top throughout the remainder—in fact the whole—of the turn to starboard is denoted by the small, dotted circle in Fig. 7, and any chord of this circle from point A indicates the real tilt of the gyro axis in relation to the true vertical. For example, A-B' represents the direction of tilt after turning 90° to starboard, etc. Since the relationship between the axis top and the true vertical varies during the turn, the nature and extent of indication error vary accordingly.

Compensation for Pendulosity Errors

28. Fig. 7 also shows the locus of the gyro axis top of an artificial horizon that has been compensated for pendulosity errors by having the fore-and-aft pendulous vanes counter-balanced to impart to the rotor axis top a constant 1½° tilt to port. It is seen from Fig. 7 that this compensation causes the axis top to revolve about point A during the turn, giving a constant tilt relative to the aircraft heading, and thus a constant error. The latter is, in turn, corrected by modification of the horizon bar lateral setting to register zero bank during laterally level flight, when the rotor axis top is inclined 1½° to port of the true vertical, and thus to give a true indication of the angle of bank during turns.

Residual Errors

29. It has been shown that it is possible to cancel out the precessional effects of centrifugal force on the artificial horizon by employing compensating tilts and minor structural modifications. In practice, however, small residual errors, due to friction and the combined effects of erection and pendulosity, may remain. These errors are very small in comparison with the errors already corrected, and the instrument may be said to indicate accurately for the selected speed and rate of turn for which it has been compensated, *i.e.* 174 knots (200 miles per hour) and Rate One. At other rates of turn there will be small errors, but these will be much less than those in an instrument in which the axis of the gyro has not been compensated.

Limitations

30. **Temperature Limits.** Both the Mk. 1 and the Mk. 1B artificial horizons are suitable for use at any temperature between -40°C. and +60°C.

31. **Minimum Time Limit for Reliable Indications.** Although the rotor does not attain its full speed until the correct suction has been applied for at

least four minutes, the indications can usually be relied upon after the correct suction has been applied for one and a half minutes.

32. **Flight Operating Limits.** The Mk. 1 artificial horizon registers bank up to 90° in either direction and pitch up to 55° in either direction; while the corresponding limits for the Mk. 1B are 110° and 60° respectively. If these are exceeded, the gyro unit comes up against the stops, and topples. When this occurs, the horizon bar sweeps upwards and downwards across the face of the instrument, and true indications are not obtainable until the gyro settles down again, an operation requiring from 10 to 15 minutes.

Pilot's Serviceability Checks

33. **On the Ground.** Pilots should check that the dial glass is undamaged and that the horizon bar takes up a laterally level position in the correct pitch relation to the miniature image aircraft within the specified time limit, and retains this position when the aircraft is turned during taxiing. If a caging device is fitted, the instrument should be uncaged at least four minutes before take-off to allow the horizon bar to erect correctly.

34. **In the Air.** Pilots should ensure that the artificial horizon gives an immediate and correct indication of any changes in the pitching and rolling attitude of the aircraft.

MK. 1D

35. The Mk. 1D artificial horizon, of which constructional details are given in the Instrument Manual, operates on the same basic principles as the Mk. 1 and Mk. 1B, but from the pilot's viewpoint it differs from the earlier artificial horizons in the following main features.

Operating Suction and Rotor Speed

36. The correct operating suction is 3½ to 4½ inches of mercury, which gives a rotor speed of approximately 25,000 r.p.m. (Direction of rotation is the same as that of the earlier models.)

Minimum Time for Reliable Indications

37. Full rotational speed is not attained until the correct suction has been applied for some four minutes, but as the rotor speed is not critical the instrument can be used as soon as the horizon bar has settled down. This should not take more than two minutes.

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Operating Limits

38. The Mk. 1D is suitable for use at cockpit temperatures between -20°C . and $+50^{\circ}\text{C}$. It has complete freedom of movement in roll, and freedom of movement up to 85° in dive and climb. In practice, however, the instrument is almost fully aerobatic since toppling rarely occurs except during a perfect loop. When toppling does occur, re-erection starts immediately and should be completed within one and a half to three minutes.

Pilot's Serviceability Checks

39. Before flight, pilots should check that the dial glass is undamaged and that the horizon bar takes up a laterally level position in the correct pitch relationship to the image aircraft within the specified time limit, and retains this position when the aircraft is turned during taxiing. During flight the artificial horizon should give an immediate and correct indication of any changes in the pitching and rolling attitude of the aircraft.

MK. 1E (SPERRY TYPE)

40. The Mk. 1E (Sperry Type) is basically similar to the Mk. 1B artificial horizon. There are a number of constructional improvements in the Mk. 1E, however, and these are fully described in the Instrument Manual. From the pilot's viewpoint the salient features are as follows.

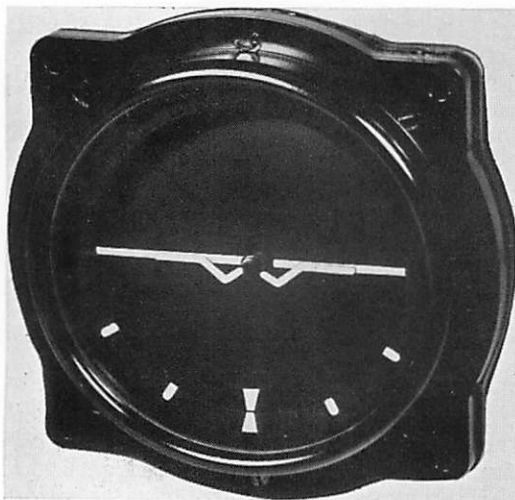


Fig. 8. Artificial Horizon, Mk. 1E.

Presentation

41. The image aircraft is a miniature "gull-wing" aircraft having wing sections at 30° and 45° to the horizontal, when, as shown in Fig. 8, the instrument is indicating level flight. The gull-wing shape assists bank angle estimation and all sections of the image aircraft wings are thinner than on the earlier models, thereby permitting finer control adjustments to be made during flight. A further improvement in presentation is the elimination of the outer gimbal ring support bracket from the dial face, which has been achieved by attaching the rear pivot of the outer gimbal ring to the centre of the glass dial cover.

Operating Suction and Rotor Speed

42. The correct operating suction is $3\frac{1}{2}$ inches of mercury, with a tolerance of $\pm\frac{1}{2}$ inch of mercury. This spins the rotor at between 14,000 and 15,000 r.p.m. anti-clockwise when viewed from above.

Minimum Time for Reliable Indications

43. The time for erection depends on the initial attitude of the gyro assembly and the value of the suction applied to the instrument. Erection should normally occur within two to five minutes, but the instrument indication is usually reliable after the correct suction has been applied for one and a half minutes.

Operating Limits

44. The instrument is suitable for use in temperatures from -55°C . to $+70^{\circ}\text{C}$. It has flight operating limits of $\pm 85^{\circ}$ in pitch, but permits complete freedom in roll. If the flight operating limits are exceeded, one or other of the screw stops strikes its resilient stop and topples the gyro. When this occurs the horizon bar sweeps upwards and downwards across the instrument dial and true indications are not obtainable until the gyro settles down again, an operation requiring up to 11 minutes.

Pilot's Serviceability Checks

45. The checks for this instrument are identical to those for the Mk. 1D.

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