J. Exp. Biol. (1970), 53, 187-193
With 5 text-figures
Printed in Great Britain

MODIFICATIONS IN THE AUTOMATIC DIVER BALANCE TECHNIQUE

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(*Received* 16 *March* 1970)

The automatic electromagnetic diver balance, described by Larsson & Løvtrup (1966), is based on the principle that a diver with density less than the surrounding medium is prevented from rising to the surface by an electromagnetic force acting on a small piece of iron placed in the diver. Since it was first introduced, the balance has displayed certain imperfections which have hampered experimental progress. The primary causes of these disturbances have been traced to temperature oscillations in the flotation medium, to details in the electronic design and to the magnetic materials used in the core and in the diver. In the course of the work to remedy these sources of trouble our understanding of the theory of the method has greatly improved and as a consequence we have been able to devise other innovations which enhance the precision of the method. This report presents in brief outline the theory and the various modifications introduced.

Theory of the diver balance

In a non-uniform field a magnet will experience a translational force as well as a torque, because the force pulling in one pole parallel to the field will be opposed by a different force acting on the other pole. If the gradient of the field is dH/dx, the force F on a magnet of moment M is

$$F = M\,dH/dx. \tag{1}$$

The moment M is equal to Iv where I is the intensity of magnetization and v is the volume of the magnet.

In the ideal case linearity obtains between the field strength H and the current i in the coil. In the following discussion this assumption is adopted; in a later section it will be shown how this situation is realized in practice. As a consequence we have

$$dH/dx = ki. \tag{2}$$

Combining (1) and (2) and introducing the expression for M we get

$$F = kIvi. \tag{3}$$

The equilibrium condition for a floating diver is

$$-RW_d - RW_x = kIvi, \tag{4}$$

where RW_d and RW_x stand for the reduced weight of the diver and load, respectively (cf. Larsson & Løvtrup, 1966).

As it turns out, k in (4) is not constant because the diver moves in the magnetic field; rather, it must show the dependence:

$$k = C(L-h)^{-\mu}, \tag{5}$$

where C is a constant, L the distance from the coil to the magnet in the unloaded diver and h the displacement due to loading. The value of the exponent μ ranges between 3·5 and 4.

Unless the magnetic material in the diver is completely saturated, I is not constant either. The reason for this is as follows. When a body is magnetized by an applied field, H^*, its ends carry magnetic poles which generate a magnetic field ΔH in the direction opposite to H^*. The effective field acting on the body is then the difference between these two fields:

$$H = H^* - \Delta H. \tag{6}$$

ΔH is approximately proportional to the intensity of magnetization, thus

$$\Delta H = NI, \tag{7}$$

where N is called the demagnetizing factor. The latter depends on the geometry and can be calculated accurately only for specimens of ellipsoid form. Bozorth (1951) gives a table of the demagnetizing factor for rods with different ratios between length and diameter, from which it appears that the factor decreases when the ratio is enlarged. When the latter parameter is known, it is possible to calculate the field strength required to saturate a specimen with known magnetic properties.

The practical application of these theoretical considerations will be shown in some of the following sections.

Temperature regulation

The buoyancy of a floating diver is proportional to the difference in density between the flotation medium and the diver proper, which entails that it is very sensitive towards temperature changes. The small value of the buoyancy relative to the volume (~ 100–300 μg/60 μl) implies that the equilibrium may easily be disturbed by convection currents. As described in the previous paper, the flotation vessel is placed in a bath with circulating water, which is immersed in a large bath in which the temperature is regulated better than ± 1/100°C. There is no doubt that this set-up is adequate, provided loss and supply of heat are prevented in the flotation medium. As far as the first point is concerned, surface evaporation suffices to cause a measurable change in temperature, and the vessel must therefore always be covered. Heat is generated in the magnet situated beneath the flotation vessel. In the original diver balance the magnetic core touches the bottom of the flotation vessel, and the heat thus conducted causes the generation of convection currents in the flotation vessel. To avoid this source of error, part of the circulating water in the inner bath is passed through a metal tube separating the magnet from the flotation vessel (Fig. 1).

Amplifier design

It was pointed out in the theoretical section that when a diver is displaced upon loading it moves from a weaker to a stronger magnetic field. As a consequence the reduction in current associated with the loading comprises two components, one due to the decrease of the buoyancy of the floating system and one due to the change in the field strength. For small loads the resulting standard curve is approximately linear, and under these circumstances the extra reduction in the current may be advantageous in so far as it increases the sensitivity of the method. However, with increasing load the standard curve deviates more and more from a straight line (Fig. 2).

This lack of linearity makes the evaluation of the results rather cumbersome. One way to circumvent this inconvenience is to increase the amplifier gain, entailing that the displacement for a given load is reduced. In the original version this adjustment is coupled with a reduction of the height of the light beam, so that the empty diver floats closer to the lower edge of the latter. However, under these conditions, loading of the diver may easily result in the diver temporarily cutting off the light beam completely. If this happens, the servo-system no longer works and the diver sinks to the bottom.

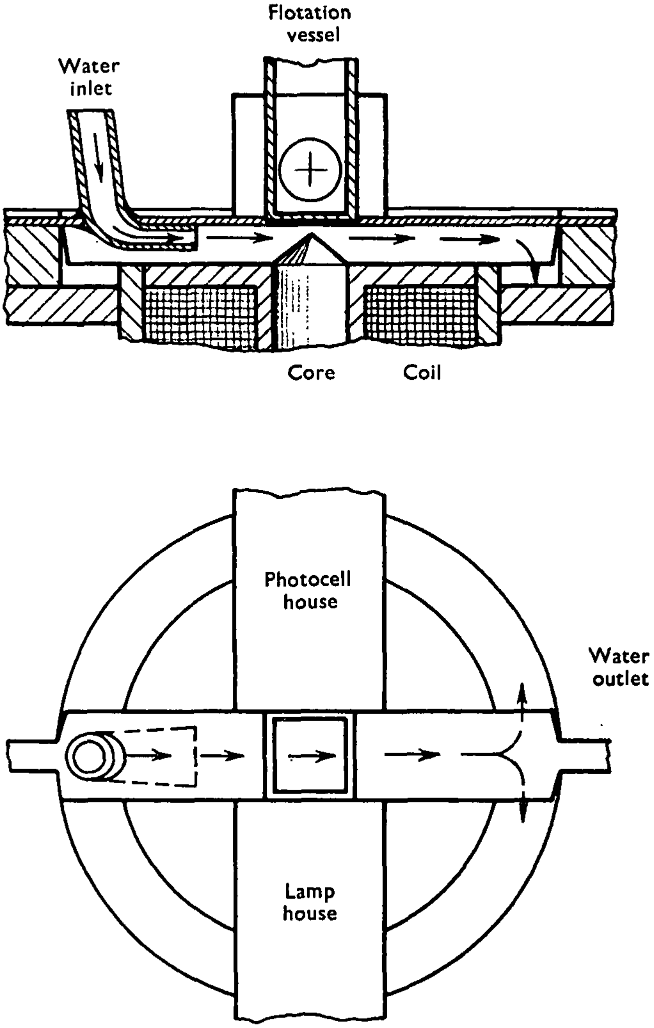

Fig. 1. Diagram showing the arrangement for water circulation between the magnetic core and the flotation vessel.

To improve upon this situation, various changes have been introduced in the electronic design (Fig. 3). The new servo-amplifier works on the basis of d.c. operational amplifiers. The photocell generates a d.c. which is amplified and converted to

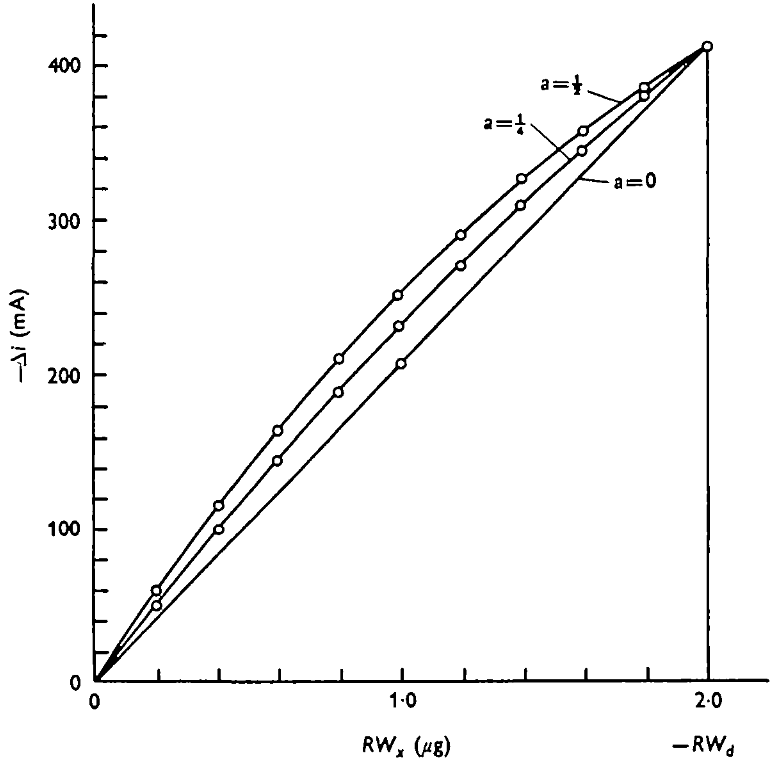

Fig. 2. Calibration curves for a diver with a value of $-RW_d$ = 2·0 mg., calculated from the equation $i = A(RW_d - RW_x)(L-h)^{\mu}$ obtained by combining equations (4) and (5). The following assumptions were made: $A = 1/CIv$ = constant, L = 10 mm, μ = 4 and $h = aRW_x$. The curves shown correspond to the values 0, 0·25 and 0·50 for the proportionality factor, *a*.

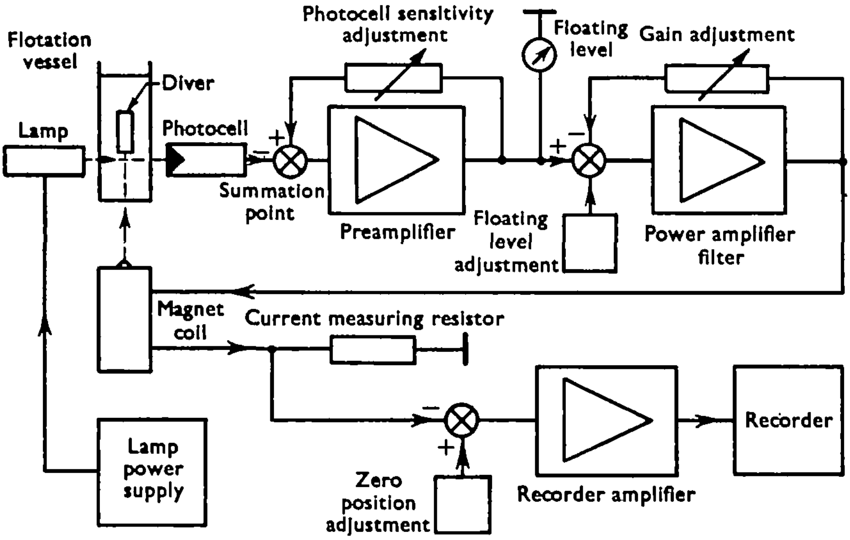

Fig. 3. Block diagram of the new servo-amplifier design.

a d.c. voltage in the pre-amplifier. This signal is compared with a reference voltage and the difference is amplified in the power amplifier, the output of which feeds the magnet coil. With this construction it is possible to work with the diver at any desired level and at the same time change the amplifier gain at will.

The feedback system diver-amplifier may occasionally begin to oscillate, and the probability of this event increases with the degree of amplification. In order to suppress these oscillations an electronic filter has been incorporated in the power amplifier.

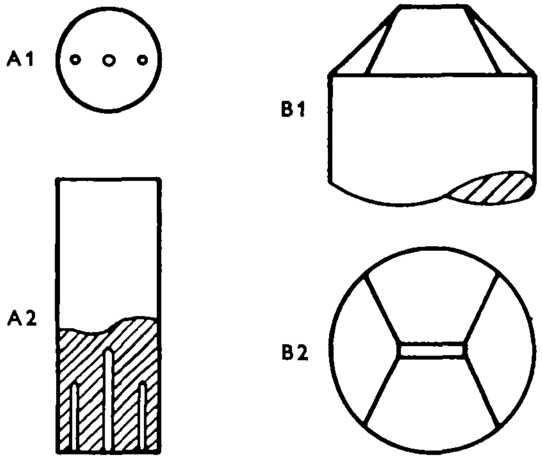

Fig. 4. (A). The new design of the diver seen from below (1) and in section (2). In the central hole of the polypropylene body a piece of platinum wire is inserted to adjust the loading capacity of the diver ($-RW_d$). In the two other holes are inserted pieces of Permalloy. (B) The tip of the magnetic core, made of soft iron, seen from the side (1) and from above (2).

The magnets

It has been observed that the divers may rotate in the flotation vessel. Since it is physically impossible to make the lower surface absolutely plane, this rotation may cause slight changes in the equilibrium current. To suppress this source of error, two modifications have been introduced, namely the tip of the core is made wedge-shaped, and two magnets are inserted in the diver (Fig. 4). By these expedients rotations are prevented.

For the approach to optimal conditions regarding the linearity of the calibration curve, the magnetic properties and the geometric shape of the magnets in the coil and in the diver are of very great importance. To ensure linearity between the field strength and the current in the coil, the core in the latter must be made of remanence-free material. From field-strength measurements with a Bell 120 Gaussmeter we have convinced ourselves that ordinary soft iron works perfectly well for this purpose.

The strength of the magnet in the diver ought to be constant. For that reason we have previously employed Koerzit T, a permanent magnetic material. Unfortunately, when placed in the magnetic field of the coil it will exhibit a hysteresis curve because the field strength is too weak to saturate the Koerzit. From a theoretical point of view it is therefore much more desirable that the external magnetic field induces the diver magnet. If the latter is made from a material with low coercive force, the strength of the magnet will be constant over most of the working range. We are now using Permalloy for the diver magnets, which has a coercive force of about 0·1 G. This implies that as long as the effective field (cf. equation (6)) is above this value the magnet is independent of the applied field. It will be realized that at low-field strengths linearity no longer obtains between load and deflexion. The calibration curve will therefore assume the course shown in Fig. 5. As mentioned above, it is possible to minimize this demagnetization effect by increasing the ratio length: diameter of the diver magnets. We therefore use Permalloy threads with a length of 1–3 mm. and a diameter of about 0·1 mm. Little is gained by increasing the ratio beyond this range. Since it is impossible to obliterate completely the demagnetization effect, it is necessary to determine for each diver the maximum load compatible with a linear standard curve.

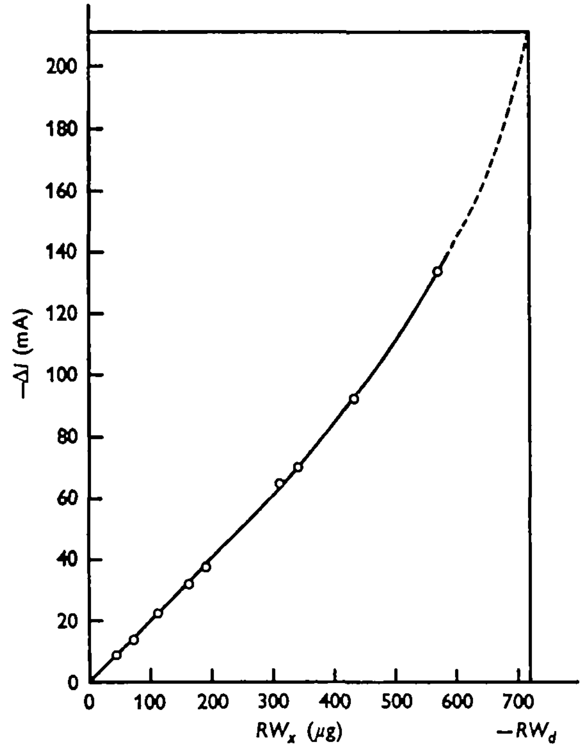

Fig. 5. Experimentally established calibration curve for a diver with $-RW_d = 720\ \mu g$. It is seen that in this particular case the curve is approximately linear during the lower half of the working range. If, for the same amounts of polypropylene and Permalloy, less platinum had been employed, the calibration curve would be extended linearly to the left.

SUMMARY

1. Various improvements in the diver-balance technique are described, which are based partly on an improved knowledge of diver-balance theory and partly on practical experience.

2. Certain theoretical aspects concerning the strength of the magnetic field and the force prevailing between this and the diver magnet are outlined.

3. Devices for improving the temperature constancy in the flotation vessel are described.

4. A new electronic design of the amplifier has been devised, which makes it possible to adjust the gain without changing the flotation level, and which efficiently suppresses diver oscillations. With this equipment it is possible to work with high amplifier gain, which implies that the displacement due to loading is so slight that the calibration curve approaches linearity.

5. To prevent rotation two magnets are introduced into the diver, and the tip of the core is made wedge-shaped. The latter is made of remanence-free material. The magnets in the diver are made of material with low coercive force, and they are shaped so as to minimize the demagnetization.

We gratefully acknowledge the assistance of Miss Ulla Berg, Mr André Berglund, Mr Börje Engström and Mr Lars-Erik Sandström in various aspects of the present work. The research programme was supported by a grant (2240-18-7990 B) from Statens Naturvetenskapliga Forskningsråd.

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