(*Paper No. 3959.*)

**"The Accelerometer, and its Application to Railway
Traction Problems."**

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(*Abridged.*)

MANY attempts, some successful, have been made to produce an instrument to measure acceleration. Methods employing the pendulum, or the spirit level, have been the most common, but the readings were liable to be vitiated by fluctuating forces acting in directions transverse to that in which the measurement was desired. Thus a pendulum having a displacement from the vertical, due to the vehicle carrying it becoming subject to a horizontal acceleration, will also be affected by any vertical acceleration which the vehicle may be experiencing at the same time. And it is noteworthy that the vertical accelerations sometimes exceed that of gravity and are usually much larger in amount than the horizontal accelerations which it is desired to measure. The "spirit level" form of instrument is affected in the same manner.

Now it happens that the practical cases where the measurement of acceleration is desired, say on a railway train, a tramcar, or other moving vehicle, are just those where very large lateral and vertical disturbing forces are likely to arise. The motion of the springs of the vehicle introduces very large vertical accelerations, whilst the cant of the road, or the centrifugal action on rounding a curve, may introduce lateral accelerations exceeding 10 feet per second per second.

USES OF AN ACCELEROMETER.

The first step therefore towards making the accelerometer into a practical instrument is so to arrange its mechanism that it is affected only by accelerations in the required direction. This problem the Author set himself to solve, and with the invaluable practical aid of Mr. G. K. B. Elphinstone, of Messrs. Elliott

Bros., a solution was found. There were, of course, other difficulties to be overcome, such as making the instrument dead-beat in its movement, compact and handy in its size; but these were not troublesome. Before describing the principles of its action and construction, it is necessary to specify the uses to which such an instrument may be put. These introduce considerations which need to be borne in mind when discussing the constructive details. In addition to measuring the forward acceleration of trains and other moving vehicles, accelerometers are also used to measure:—

1. The retarding force due to the application of the brakes;
2. Train-resistance;
3. The accuracy of lay-out of railway transition-curves, and the permissible speed on any given curve.

The instrument is also able to measure the tractive effort required for the propulsion of road motor vehicles,¹ road gradients and the angle of inclination of a rolling ship.

The utility of making measurements of the acceleration and braking of trains lies in this: that it reveals the condition of the motors and brakes and the degree of skill which is being used by the train operators. It is well known that unsuitable use of the controller and of the brakes leads to a large waste of energy, besides being detrimental to the life of the rolling stock and to the comfort of passengers.

Any additional means of measuring train-resistance is welcome, as adding to the opportunity of settling the long controverted questions as to the connection of resistance with speed, with train-loads and with wagon-capacities.

No. 3 of the foregoing uses is one of the most important, although not one of the best known. The instrument enables a study to be made of the balance of speed and cant throughout the line and of the accuracy with which transition-curves have been laid out; and this with a minimum of expenditure of time and trouble. It is then being used as an equilibrat, and has the advantage over earlier forms of equilibrats that its readings are unaffected by longitudinal forces acting along the train or by any vertical oscillations. A U-tube containing liquid has been used for this purpose on one of the English railways, but it has the disadvantage that it leaves no permanent record of its readings.

¹ Described in a Paper read by the Author before the British Association in 1910, and published in *The Engineer*, vol. cx (1910), p. 313.

THE WIMPERIS ACCELEROMETER.

The principle of action of this instrument has been fully described in the Author's previous Paper referred to, but a short summary will not be out of place here, as it is quite different from that of any others; although those who work at this subject cannot but be indebted to the careful work of such inventors as Desdouts, Lanchester and Trotter. The instrument is made either for direct-reading use or as a recording instrument.

The general nature of the internal mechanism (*Fig. 1*) may be described as a lop-sided copper disk, mounted on a vertical axis and controlled in its rotation by a coiled spring (not shown). Any acceleration causes the heavier side of the disk to lag behind, and so partially to

wind up the spring. The degree to which the spring is wound up measures the acceleration. To the pivot of this disk is fastened a spur-wheel which gears in with another equal spur-wheel mounted on a parallel axis and carrying the pointer; this combination forms a compensating device. Thus, if a second acceleration should be acting at right angles to the first, there would be an additional couple tending to wind (or unwind) the spring. Were this not compensated for, the needle would give false indications of the acceleration

tion which it is desired to measure. To meet this difficulty, the two gear wheels are added, and it is so arranged that their mass-moments about their two respective axes are equal. The equality of mass-moments makes the system equivalent to two equal copper disks geared together at their circumferences, and each having their centres of gravity eccentric to the same extent. The effect of this is illustrated in *Fig. 1a*, from which it will be seen that forces in the direction P will cause the two disks A and B to roll together, whilst forces in the direction Q cause no rotation whatever. Forces perpendicular to the paper can, of course, produce no rotation of the disk, so that the instrument records the acceleration in one of the three directions of space only, and is not affected by whatever may be happening in the other two. Thus the dial may

even be tilted until it is vertical, so that the whole force of gravity acts across it without the readings being at all affected.

It will be seen that any tendency of the disk to oscillate is checked by a magnetic field at right angles to the plane of the disk. The effect of the high frequency vibration of a train is to cause ripples on the trace which the pen of the instrument produces. The amplitude of these ripples is proportional to the actual linear displacements and in phase with them. It is not difficult to show analytically¹ that a forced vibration is reproduced, to a smaller scale, on any such system as this, when the frequency of the forced vibration is much larger than that of the free vibrations of the system. Further, when the contrary holds good, the displacement of the vibrating system at any moment is proportional to a term containing the square of the frequency of the forced vibration, and therefore to the impressed acceleration. (It is, indeed, this difference of natural frequencies which distinguishes seismographs from accelerometers.)

The earlier forms of the instrument were made exactly as described, but in the later models it was found better to modify the construction to one more easily manufactured. The principle of action is precisely that already given, but the greater part of the disk is cut away and only segments are left. These, as before, are magnetically damped. Adjusting weights are added, the position of which can be altered till the mass-moments about the two axes are brought to exact equality. In the recording models the paper is fed by clockwork, usually 1 or 3 inches per minute as may be desired. The needle is, of course, longer in this form than in the indicating instrument, and this gives a linear ratio between the height of the recorded curve and the acceleration, so that no special scale has to be used. In all models a levelling screw is fitted to enable the needle to be adjusted to the zero when the vehicle is standing on a level track. No other levelling is needed.

Fig. 1a.

MEASUREMENT OF ACCELERATION AND BRAKING.

A great number of tests, particularly on railways, have been

¹ See Professor B. Hopkinson. "Vibrations of Systems having One Degree of Freedom." Cambridge Engineering Tract, No. 1 (1910), pp. 14-16.

taken by the Author and by others, and some of the curves are here reproduced. The curve obtained during the running of a steam-train on the London, Brighton and South Coast Railway between Balham and Streatham Hill is shown in Fig. 2, Plate 8, and corresponding curves for electric railways are given in Figs. 3, 5 and 6, Plate 8. The contrast between the starting acceleration on the steam and electric railways is marked, as is that between the alternating-current system of Figs. 3 and 3a with the direct-current systems of Figs. 5 and 6. The acceleration on the electrified Brighton line is a good deal steadier and less "ragged" than that on the others. The gaps in the acceleration curves of the Metropolitan Railway are attributed to slowness in changing from series to parallel.

It will be seen that the steam-train acceleration is only about one-third of that of any of the three electric systems. On the other hand, the amount of the braking is about the same, although different in character; the curve of braking on the steam-train shows two distinct parts: the earlier one shows the effect of a partial application of the automatic brakes and the latter the complete application of the brake. The braking curve on the Baker Street-Waterloo tube, as shown in Fig. 5, is a good one; it is well rounded, and the braking effort is gradually eased off. In Fig. 6 the braking curves are not satisfactory, as the curve rises to a sharp point and the train stops with a very unpleasant jerk. The braking curves on the electrified Brighton line come between these two, although what is perhaps the nearest to the ideal of braking is found in the stop at Battersea Park in Fig. 3, while the worst is undoubtedly that at the stop at Willesden Green shown in Fig. 6a. The ability to make automatic records of these features of train operations should materially assist in any efforts at their improvement.¹

Curves of time and velocity are best obtained by direct measure-

¹ On the sudden releasing of the braking effort due to the stopping of the train, there necessarily is a tendency for the needle to be set swinging until it is brought to rest by the friction of the pen on the paper. The proper setting of the pen is easily discovered by a little practice; it is necessary, on the one hand, to avoid too much pen friction (as that would give lagging indications), and on the other hand, too slight a contact (as that causes the pen to chatter and swing). Train vibration greatly diminishes the pen friction, but when the train is at rest this useful effect ceases. This explains why the pen tends to return somewhat slowly to its zero when standing in the station, an effect that can be seen at the stopping places in most of these curves. The zero to which the pen desires to return—and to which it always does come within 5 seconds from the stop—is of course a reading equivalent to whatever may be the gradient in the station, thus Figs. 3 and 3a show the station at Battersea Park to be practically level, and that at, say, Peckham Rye to have a slight rise towards the next station on.

ment, but they can be got indirectly from acceleration diagrams by measuring the areas of the acceleration diagrams and by making allowances for the various gradients along the line; thus *Fig. 4* shows the result of using this method for the service on the electrified Brighton line between Battersea Park and Wandsworth Road.

Although the instrument can, if desired, be used to indicate the gradient on which a train is standing or on which it is proceeding at a uniform speed, the acceleration and braking readings do not need correction on account of those measurements having been made up or down hill. The explanation of this is, that when descending a gradient the slope tends to throw the heavier side of the disk forward, whilst the gravitational acceleration due to the gradient

Fig. 4.

SPEED-TIME DIAGRAM FOR RUN FROM BATTERSEA PARK TO WANDSWORTH ROAD
(L.B. & S.C.R.).

throws it in the opposite direction by just an equivalent amount, so that the two effects neutralize one another; and were the train coasting with no resistance to motion, the instrument would indicate zero, no matter what the gradient or how high the speed. What, in practice, causes the needle to move away from the zero mark when coasting is the resistance due to motion; the needle therefore shows the amount of this resistance, no matter whether the train is on a sloping track or not. As a matter of practical convenience it is best to make resistance measurements when coasting on a slight downward slope, as the speed then changes more slowly, giving a longer time for taking the readings, and the complicating effect—familiar to railway engineers—of the change in the momentum stored in the rotating wheels of the train is then insignificantly small.

Under any condition of gradient therefore the instrument will always show the acceleration, or retardation, proportional to the net tractive effort of the engine, the brakes and the resistance, and a knowledge of the gradient is unnecessary. This is dealt with more fully in the British Association Paper referred to, where measurements made in this way are also given.

MEASUREMENT OF TRAIN-RESISTANCE.

Many measurements with this instrument have now been made of track-resistance on railways and roadways, and in this is included any air-resistance there may be. In the case of train-resistance measurements a specially fine control-spring is fitted. In a recent instance the Author measured the train-resistance at about 65 miles per hour as from 19 lbs. to 21 lbs. per ton, rising to 30 lbs. on some curves, and sinking to 10 lbs. at about 10 miles per hour. These were all estimated speeds, but a series of very careful tests has been made by Mr. Philip Dawson, M. Inst. C.E., on the electrified section of the Brighton Railway, both by the usual method and by the simpler method of the Author's accelerometer. These tests were described in a Paper¹ read before The Institution by Mr. Dawson, from which the following figures, obtained by accelerometer measurements on a three-coach train, have been taken:—

Speed. Miles per Hour.	Train-Resistance. Lbs. per Ton.
1	4·8
5	6·1
9·7	7·0
35	9·3
40	16·0

The Author has also used this method to note the extra resistance due to picking up water from a water-trough on the line, and finds it usually to be from 8 to 10 lbs. per ton at about 50 miles per hour, thus absorbing a very large part of the total tractive effort which the engine could exert at that speed.

THE USE OF THE INSTRUMENT AS AN EQUILIBRISTAT.

To use the accelerometer as an equilibratist it is only necessary to turn it bodily through 90° in a horizontal plane, i.e., to arrange it so that the pen moves across the train instead of in the direction of the length of the train. It is then affected both by lateral acceleration

¹ "The Electrification of a Portion of the Suburban System of the London, Brighton and South Coast Railway." Minutes of Proceedings Inst. C.E., vol. clxxxvi, p. 46.

and by any superelevation, intentional or accidental, of one rail over the other, and affords therefore a speedy way of checking the accuracy of the balance between speed and cant. This use of the instrument has therefore an important bearing on the safety of the line so far as the speed around curves is concerned. In Figs. 7 and 8, Plate 8, are given extracts from a curve obtained during a run on an express train from London to Guildford and back on the London and South Western Railway. The speed at the moment and the lay-out of the line are given below the equilibratistat curve, which curve shows the balance of centrifugal force against superelevation. The speed of the Paper is reproduced at about 2 inches per minute. If the superelevation were always exactly of the amount required by the theoretical formula for the given speed and curve, the needle would always indicate zero, since the centrifugal force would then be exactly balanced by the cant. It will be seen that this is rarely the case, although there will be noticed an excellent stretch in Fig. 8*b*. It will be seen that the departure of the needle from the zero line is never very great, and is never long maintained. Probably most of the variations in Fig. 7 are due to slight inequalities in height of the two rails, and these seem to be unusually numerous between the third and fifth miles.

In Figs. 7*a* and *b* (showing the return journey on the other pair of metals), however, there are some much more considerable variations, and there can have been little superelevation around the 20-chain curve between the second and first miles. The absence of superelevation in such a case as this is not thought to be of such exclusive importance as it once was. The practice now is to pay attention not only to the amount of superelevation in relation to speed, but also to the *rate* at which the cant and lateral acceleration change from a high value to a low value or vice versa. Thus an important feature of this curve is the sudden movement of the pen upon entering it, showing in as little as 3 seconds a rise equal to 2.8 feet per second per second, or a rate of increase of almost 1 foot. This is probably as high a value as is generally desirable in the interest of passengers and rolling stock alike.¹

¹ See W. H. Shortt, "A Practical Method for the Improvement of Existing Railway Curves," Minutes of Proceedings Inst. C.E., vol. clxxvi, p. 100, where it is stated that: "An efficient transition curve should allow of a rate of gain or loss of" (lateral) "acceleration, for the fastest trains, just equal to the maximum amount that will pass unnoticed, and its length in all cases should be such as to permit of this. . . . In the Author's experience a rate of change of acceleration of 1 foot per second per second in a second is the maximum that will pass unnoticed."

In Fig. 7*b* is shown a cross-over taken at about 30 miles per hour, which gives a rate of change of twice this amount. At the twenty-sixth mile in Fig. 8 is seen a rapid rise in the equilibristat curve from -2 to nearly $+2$ feet per second per second, but the slope of the curve is gradual and no harmful results would be expected. The curve in Fig. 8*a* is due to the train suddenly entering a curve out of the main line at 47 miles per hour. There was, of course, no superelevation and the rise in lateral acceleration is exceptionally pronounced and is somewhat ragged. The rate of rise of the curve is certainly very much above 1 foot per second per second in a second, and the blow received by passengers and stock alike must be correspondingly great. These curves are all on a time base, but they can be drawn if desired on a distance base, by causing the paper to feed at a rate proportionate to the train-speed. This does not make the instrument quite so portable but is sometimes preferred. A point to be borne in mind is that, in the case of the cant and speed being much out of balance, the lateral give of the carriage springs tends somewhat to increase the tilt of the floor of the car, and this tilt of course is felt by the instrument; the carriage springs tend also to lessen the sharpness of the blow on a badly laid-out road, but these effects are all of them felt by the passengers, and the instrument records the net effect. The equilibristat use of the instrument affords therefore a convenient guide as to the safety of lay-out of any given piece of track in relation to the train-speeds used or proposed to be used on it. It is also a guide in cases where improvement in the comfort of travelling is thought necessary or found to be advisable.

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The Paper is accompanied by eight drawings, from which Plate 8 and the Figures in the text have been reproduced; also by several photographs.

THE ACCELEROMETER.

Fig: 3.

Fig: 3^a.

Fig: 5.

Fig: 6.

Fig: 6^a.

PLATE B.
THE ACCELEROMETER.

Fig: 7.

Fig: 7^a.

Fig: 7^b.

Fig: 8.

Fig: 8^a.

Fig: 8^b.