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A METHOD OF BALANCING, REVOLVING, AND RECIPROCATING WEIGHTS IN LOCOMOTIVES, AS APPLIED TO INSIDE CYLINDER ENGINES.

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The subject had been chosen by him as one that might be of interest to members generally, and though applied in this case to locomotives, his object was to place before them something which would promote discussion and interchange of ideas, and to his mind it was one of which all mechanical men should possess some knowledge, not merely from a theoretical point of view, but from a practical standpoint, and based upon the latter lines he venture to approach.

The balancing of revolving and reciprocating weights in locomotive engines had at one time and another given rise to a fair amount of discussion through the columns of "Engineering," and, notwithstanding all he had read on the matter, his own opinions were formed from experience gained, careful working out so as to ascertain the correct amount of balance, where it should be placed in the wheel rim, and how to arrive at such a decision, so that the effect of the disturbing forces set up by the engine when running on the road might be neutralised. Before describing in detail the method adopted as a solution of the problem, he might state that in designing an engine for passenger service, it was a matter of some importance for the engineer to determine in his own mind what proportion of reciprocating forces, as well as the whole of the revolving weights, could be effectively balanced by the application of a minimum amount of material placed near the wheel rim, and to so adjust the weights as to obviate hammer-action on the rail surface. The inside cylinder engine rendered this feature practicable to a very great extent, and specially so where cast steel wheels were used, permitting the balance weights to be cast in the wheels and formed of a lune or crescent shape would as will be seen form the diagram. It would be easily understood that the vertical disturbing forces arising from heavy balance weights produce hammer-action on the rail surface, and in quick running engines, unbalanced or only slightly balanced, reciprocating force produced unsteady riding of the engine.

Various engineers differ in opinion with regard to the actual amount of the reciprocating forces to be balanced, so much so that they varied from half to two-thirds, and even three-quarters of the actual forecs in passenger engines; in goods engines from one-third to one-half, and it might be of interest to note to what extent opinions diffiered among men who had opportunities of observing practical results. Professor Unwin said balance none of the reciprocating weights, Professor Perry said balance all, and Professor Rankine said balance all, and the latter gentleman had even gone so far as to suggest suspending an engine, running it and placing counter-weights in bit by bit until proper balance was obtained, but he was not aware whether this idea was carried out or not. Personally he did not think the theory advanced would meet the conditions under which an engine would run on the road. It was often found that the wheels of goods engine were too small to permit of the revolving weights being balanced to the full extent, but in the case of slow running engines this was not a matter of great importance, and as he was only going to deal with a passenger service engine, he would not attempt to enlage upon that part of the question at present.

If a horozintal reciprocating force be one-third balanced by a revolving weight the disturbing forces will be equal horizontally and vertically, for horizontally the disturbing force will be due to the inertiaof the unbalanced part of the reciprocating force, and vertically the disturbing force will be due to the centrifugal force of the revolving weights, which is equal to one-half of the reciprocating force, and it was best to balance reciprocating force, where possible, by other forces transmitted along the coupling rods of an engine.

In the case of inside cylinder engines, it frequently occurred that a surplus in the crank boss of the trailing wheels, of a four-coupled engine was available for that purpose, and under these circumstances, a light balance weight was permissible in these wheels; a matter of some importance and one that should not be lost sight of.

He might here mention a case, described in "Engine-eirng," of an engine which had the whole of the revolving weights, and only one-half of the reciprocating weights balanced throughout the coupled wheels, and it ran steadily at 300 revolutions per minute. An accident happened to the valve gear which necessitated it running with one cylinder, and it was observed with some surprise that the engine ran nearly as steadily as before; the explanation was, that the stopping of one piston, connecting rod, &c., merely reversed the direction of the disturbing force without increasing it, and thus proved the soundness of balancing the whole of the revolving weights in each wheel separately, and equally dividing the counter-weight due to a proportion of the reciprocating parts. It was a recognised fact by all engineers having had practical experience that reciprocating forces could not be completely balanced by revolving weights, owing to the different velocities with which the reciprocating parts changed their direction at the front and back end of each stroke, but there was no difficulty where both motions could be separately provided for. However, in locomotives this could not be done without complicating the mechanism of the engine; therefore it remained for a fair proportion of these parts to be balanced as far as practicable by the revolving weights.

It would probably be within the minds of some of the members of this Association that some years ago an attempt was made on the Victorian railways to balance the whole of the reciprocating weights in a locomotive by placing exceptionally heavy weights in the wheel rim, with the result that the permanent way was seriously disarranged for several miles; and from this fact alone it would appear that engineers should exercise every care and give a preference to something within the mark rather than overbalance engines. From his own personal experience in connection with the very best locomotive practice of British builders, he ventured to say that they were all guided in this direction, and it was doubtful if you will find more than two-thirds of the reciprocating forces balanced as a maximum by any of them, and he thought in some cases you may find less. Of course, you must understand he was not now including any of the railway companies, as he was inclined to think some of their engineers did very extraordinary things in the way of balancing, and cases were known of engines having the right hand crank leading, balanced accordingly, being changed to the left hand crank leading, and the balance weights left alone in the original position, it being taken for granted that it did not create any difference, and that everything was correct. In considering the blow given by a balance weight on the rail surface it should be borne in mind that it was given gradually and more especially with lune or crescent shaped weights, and it might be necessary for him to say a few words on the uneven wear of tyres, as this formed an important part in the maintenance of the engine, and at times an item of heavy expenditure in the workshops; but this could be obviated to some extent by not balancing too much of the reciprocating forces; and for two reasons. Two causes contributed to the uneven wear of tyres. If over-balanced there was a lifting effort and a downward effort alternately with each revolution of the engine, and when the balance weight was in its highest position the crank angle might be such that when the resultant weight on rail is at its least the crank effort was approaching its maximum, and both combined to make the wheel slip at this point, and a flat place was worn on the tyre. Now, if a proper proportion of the reciprocating forces were left unbalanced it would, by tending to equalise the crank effort, make it less at the point mentioned, so that when the adhesive weight was assisted by less centrifugal force there was a reduced crank effort, and therefore less tendency to slip. So that by balancing a smaller amount of the reciprocating forces lessened the slip in two ways; first the total lifting on the wheel was less, and second the crank effort was less. Of course in treating a particular case the maximum combined crank effort must not be neglected, nor the maximum lifting effort due to both balance weights. As to wear of tyres generally, this was lessened to a very great degree by distributing the balance of the reciprocating forces between the coupled whels. Practice had proved this, and instances were known where the wear of tyres amounted to quite twice as much for certain classes of engines running with two-thirds of the reciprocating forces balanced in driving wheels alone and none of them balanced in the other coupled wheels.

He would proceed to show how masses revolving round the different vertical planes in a locomotive engine might be treated in a systematic manner, and the forces set up in these directions made to balance each other by a component force, produced from those weights requiring to be dealt with, so as to give a correct balance in each wheel at the angle or position determined.

Plate II.—Fig. 1 in elevation showed an outline of a wheel having crank A revolving at a distance *r* from centre of axle, and a counterbalance A1 revolving at distance *rl* from centre of axle. From this view alone it would appear that $A \times r$ equalled $A_1 \times rl$, or $A_1 = \frac{A \times r.}{r\,l}$ but a further review of the case shown in fig. 2, Plate II., showed that something else had to be considered, owing to the forces forming an indirect couple in the vertical planes, consequently a second counterbalance, A2, was brought into existence, which must be placed in the opposite wheel of the engine, and so adjusted that the moments of these two weights, A1 and A2, transversely, would bring their centre of gravity to the same vertical plane as that of the crank, the computation then being as follows ;—A_1 equalled $(A_1 + A_2) \times \frac{y}{x+y}$ or A_2 equalled $(A_1 + A^2) \times \frac{x}{x+y}$, and by enlarging upon this rule and taking some definite weight for A, say 400lbs,, and fixing R at 12″, R1 at 18″, X at 16″, and *y* at 40″, they obtained the values of A1 and A2 as follows :—

$$A_1+A_2=\frac{A \times R}{r\,l}=\frac{400 \times 12}{18}=266\tfrac{2}{3}\text{lbs.}$$

$$\text{then } A_1=266\tfrac{2}{3} \times \frac{y}{x+y}=266\tfrac{2}{3}\text{lbs.} \times \frac{40}{56}=190{\cdot}51\text{bs.}$$

$$\text{and } A_2=266\tfrac{2}{3} \times \frac{x}{x+y}=266\tfrac{2}{3}\text{lbs.} \times \frac{16}{\times 56}=76{\cdot}2\text{lbs.}$$

It will therefore be seen that to create a perfect balance for 400 lbs., revolving at 12″ radius from centre of axle, A1 requires to be 190·5 lbs. and A2 76·2 lbs., both placed at 18″ radius from centre of axle, and 16″ on one side and 40″ on the other transversely from centre of crank. If this could be done it would be a thorough solution of the problem for inside cranks as far as the revolving weights were concerned, but he had already stated it entails complication of parts, and it was better in practice to balance each side of the engine within itself, and place the balance weights at given angles in the wheels.

He now wished to show that by modifying the calculation and working from the centre line of engine, the result became precisely the same, and it would be more easy to follow throughout the entire system, in its application to the different parts of the engine. Having found by the first method that 400 lbs. at 12 inches radius was balanced by two opposite forces, A1 equal to 190.5 lbs., and A2 equal to 76.2 lbs. placed at 18 inches radius, and at given distances from the centre of crank transversely, the method resolved itself into the following form, treated on the principle of a beam:—

$$A_1=266\tfrac{2}{3} \times \frac{d+a}{2\,d}=266\tfrac{2}{3} \times \frac{28+12}{56}=190{\cdot}5\text{lbs.}$$

$$A_2=266\tfrac{2}{3} \times \frac{d-a}{2\,d}=226\tfrac{2}{3} \times \frac{28-12}{56}=76{\cdot}2\text{lbs.}$$

and the weight so found being applied in the reverse direction, suitable to the angle of crank, gave a set of weights in each wheel to be treated by the parallelogram of forces and composed into one weight in each wheel. He would explain this method more fully in dealing with the question generally, and to the application of the system to the whole of the engine; but ,before doing so, he might point out that in this case he was neglecting anything in the form of balance for the eccentrics and connections oin the driving wheels, as the effects of these weights were so small that in most cases they might be entirely neglected for ordinary practical purposes. Assuming the engine to be dealt with, a four-wheeled coupled one, with inside cylinders 26 inches stroke, with the outside crank bosses, coupling rods and crank pins revolving at 12 inches radius; but it must be understood that all the weights would be brought to a common radius for the purpose of facilitating the calculation.

The reciprocating weights being made up as follows:--

The revolving weights at 13″ radius in driving wheels, inside, are :—

1 Crank Pin with two Crank Sweeps	= 385lbs.
1 Large end of Connecting Rod	= 235lbs.
On plane of Crank these weights—A	= 620lbs.

The revolving weights at 12″ radius, in driving and trailing wheels, outside, are :—

1 Outside Crank Pin	= 20lbs.
½ of Coupling Rod	= 86lbs.
On plane of Coupling Rod these Weights—B	= 106lbs.

$$\text{Then B} = \frac{106 \times 12}{13} = 98\text{lbs. at } 13'' \text{ radius.}$$

One unbalanced part of Crank Boss—C = 68lbs.

$$\text{Then C} = \frac{68 \times 12}{13} = 63\text{lbs. at } 13'' \text{ radius, and re-}$$

volves on the plane of outside crank boss.

Diagrams No. 3 and 3a show end views of driving and trailing wheele, with the following dimensions :—

2a centre to centre of cylinders	2′ 4″	28″	or a 14″
2b ,, ,, coupling rods	5′ 11″	71″	,, b 35 5″
2c ,, ,, crank bosses	3′ 1″	61″	,, c 30·5″
2d ,, ,, balance weights	4′ 11″	59″	,, d 29·5″

The reciprocating weights being made up as follows, consist of :—

1 Piston with rings, rod and nut complete	= 200lbs.
1 Cross-head, 2 Slide-blocks, pins and nuts	= 120lbs.
1 Small end of Connecting rod	= 125lbs.
On Plane of Crank these weights—R	= 445lbs.

The assumption in this case was to balance two-thirds of the reciprocating weights on each side of the engine, that meant one-third in each wheel, and treating these weights as indicated by skeleton diagram No. 4, he obtained an inside reciprocating mass R equal to 455 lbs., and computing on the lines set down in the previous remarks, we obtained two values of that weight thus:—

lbs.

$$R_1 = \frac{R}{3} \times \frac{d + a}{2d} = \frac{445}{3} \times \frac{29{\cdot}5 + 14}{59} = 148 \times {\cdot}73 = 108$$

$$R_2 = \frac{R}{3} \times \frac{d - a}{2d} = \frac{445}{3} \times \frac{29{\cdot}5 - 14}{59} = 148 \times {\cdot}26 = 38$$

Having an inside revolving mass at 13″ radius, A=620lbs. for the crank and connections, we also get two values for that weight, and computing these forces on the same lines—see skeleton diagram No. 4, Plate III., we get:—

lbs.

$$A_1 = A \times \frac{d + a}{2d} = 620 \times \frac{29{\cdot}5 + 14}{59} = 620 \times {\cdot}73 = 453$$

$$A_2 = A \times \frac{d - a}{2d} = 620 \times \frac{29{\cdot}5 - 14}{59} = 620 \times {\cdot}26 = 161$$

and now working, as shown on skeleton diagram No. 5, Plate II., we get an outside revolving mass, at 12″ radius, B= 106 for half coupling rod and crank pin resolved into a weight equal 98lbs. at 13″ radius. We also got two values for that weight thus:—

$$B_1 = B \times \frac{b + d}{2d} = 98 \times \frac{35{\cdot}5 + 29{\cdot}5}{59} = 98 \times 1{\cdot}1 = 103$$

$$B_2 = B \times \frac{b - d}{2d} = 98 \times \frac{35{\cdot}5 - 29{\cdot}5}{59} = 98 \times {\cdot}1 = 10$$

and it must be born in mind these values held good, and were applicable to both driving and trailing wheels.

Skeleton diagram No. 6, Plate II., showed they had yet another outside revolving mass to deal with at 12″ radius, C= 68lbs. for the unbalanced part of crank boss resolved into a weight equal to 63lbs. at 13″ radius, this also represented two values for that weight, thus:—

lbs.

$$C_1 = C = \frac{c + d}{2d} = 63 = \frac{30{\cdot}5 + 29{\cdot}5}{59} = 63 = 1{\cdot}02 = 64$$

$$C_2 = C = \frac{c - d}{2d} = 63 = \frac{30{\cdot}5 - 29{\cdot}5}{59} = 63 = {\cdot}02 = 1$$

These values were also applicable to the driving and trailing wheels, but it might be necessary for him to point out that the difference of distance between the centres of crank bosses and balanced weights transversely was so slight, and the weights revolving very nearly on the same vertical plane, the method might almost be neglected, but as this was not always the case, he preferred dealing with the question in its entire form, and for the present it must be assumed that all these weights found were actually placed in the positions obtained it would be seen that finally such was not the case.

He would now proceed to balance both sides of the engine. Diagram No. 7, plate II showed left hand driving wheel, diagram No. 8 right hand, diagram No. 9 showed left hand trailing wheel, and diagram No. 10 right hand, and proceeding from the left hand side, the weights found to balance the engine were placed as follows in these diagrams:—To balance one-third of the total reciprocating weights in each pair of wheels, R1 equal to 108 lbs., was placed in line of the outside crank boss in left hand wheel R2 equal 38 lbs. was placed directly opposite this weight in right hand wheel. This applied to the trailing wheels also. The inside revolving weights were balanced by A1 equal to 453 lbs., and A2 equal to 161 lbs. placed in the same relative positions as the reciprocating weights. The outside revolving weights were balanced by B1 equal to 108 lbs. and C1 equal to 64 lbs. placed opposite the outside crank boss in left hand wheel, and B2 equal to 10 lbs., and C2 equal to 1 lb. were placed on the opposite side of the axle from these weights, in right hand wheel for both driving and trailing wheels. By working from the left hand side of the engine, and having arrived at certain large weights to be placed in left hand wheels, and certain small weights in right hand wheels, the same system of distribution was now applied to the weights on right hand side of engine, except that they were placed at an angle of 45 degrees in advance of those in left hand wheel, and it would be easily seen that this gave a set of balance weights in each wheel which could be composed into one by the parallelogram of forces, and so obtained a component weight at a given angle, and the actual balance weights came out as shown in these diagrams by summing up the totals found as follows:—Taking the left hand driving wheel, R1 and A1, equal to 561 lbs. to balance the revolving weights and one-third of the reciprocating forces in this wheel, these were counteracted by a weight B1 and C1, equal to 172 lbs. put in to balance the outside crank boss, half of coupling rod and crank pin, consequently 561 – 172, equal to 389 lbs. acting on the same line in the direction of outside crank boss. Then by dealing with the small weights coming over from right hand wheel, they obtained R2, A2, B2, and C2 = 210 lbs., acting at right angles in advance of outside crank boss as shown on diagram. The tangent $a = \frac{210}{389} = \cdot 54 = 28\frac{1}{2}$ degrees, and these weights composed into one force in the direction of $x = \sqrt{389^2 + 210^2} = 442$ lbs. at 13″ radius placed at the angle obtained. Having thus found the weight at 13″ radius, it could be adjusted to any size, so that the radius of its centre of gravity from centre of axle x by its weight=442 x 13. The right hand-driving wheel could be treated in a similar manner, bearing in mind the fact that the crank in this case was placed at right angles in advance of those in the left-hand wheel, and the weights must be considered accordingly.

Coming now to the left-hand trailing wheel, wherein they also balanced one-third of the reciprocating forces, they get R1 = 108 lbs. to balance these forces, and B1 and C1 = 172 lbs. acting precisely the same as previously described; but in this case the revolving weight was counteracted by the reciprocating force alone, consequently 172 – 108 = 64 lbs., acting on the same line in the opposite direction to outside crank boss. They had also in this case some small weights coming over from the right-hand wheel R2, B2, and C2 = 49 lbs., acting at right angles in advance of the crank boss, as as shown on diagram. In this case tangent $a = \frac{49}{64} = \cdot 76 = 37\frac{1}{2}$ degrees, and these weights composed into one force in the direction of x $\sqrt{64^2 + 49^2} = 80$ lb. at 13″ radius, placed at the angle obtained, and in other respects treated in precisely the same manner as the driving-wheels.

Diagrams Nos. 11 and 12 showed the wheels placed on the axles, and the relative positions of the weights so found for each pair of wheels.

He wished to point out that, in making up the calculations, he had disregarded decimal points as much as possible, and in some cases taken the nearest whole figures. In conclusion, he hoped his paper would be of some interest to the Association by promoting a fair amount of discussion.