MOTORCYCLE ENGINEERING—27

The Problem of Balance

Part 2—The Multi-cylinder Engine

By PHIL IRVING

IN the final analysis, any multi-cylinder engine amounts to a collection of singles which offers an opportunity of solving, in whole or in part, the problem of obtaining perfect mechanical balance by arranging the cylinders in such a fashion that the forces generated by one or more pistons are at any instant opposed by forces of equal magnitude but opposite in direction. The latter need not necessarily be generated by reciprocating motion, but may arise from a pair of geared contra-rotating components.

It is impossible to obtain balance when there is only one reciprocating component and one rotating component, for the former creates forces which are always in the same direction but vary in value, whereas the latter generates a centrifugal force which is constant in value but varying in direction. The methods adopted for obtaining a workable compromise were outlined in the first part of this article.

Even from that brief sketch, it should have been clear that mere duplication of the pistons is no help at all if both crankpins are in line, as they must be on a parallel-twin four-stroke to obtain even firing intervals. Despite the shorter stroke or smaller pistons, or both, the amount of unbalance is just the same as that of a single of equal capacity (Fig. 1b).

To cite a simple example, imagine two 350 c.c. engines, one a single of 68 x 96 mm., the other a twin of 68 x 48 mm., both using the same pistons. The total reciprocating weight of the twin is double that of the single, and this exactly offsets the effect of halving the stroke, so at equal crankshaft speeds the forces to be dealt with have precisely the same value.

The twin has, however, a longer crankshaft which, if of the usual two-bearing type, must be designed with great care to avoid the possibility of destructive internal vibration—a precaution less necessary with the more expensive three-bearing arrangement. The precise balance-factor to employ depends upon circumstances, but it averages about 66% of the total weight (i.e., the weight of both pistons and the upper ends of both rods). The counterweighting must be symmetrical with relation to the centre of the engine, but can be distributed between the two end webs and the central flywheel in a way which will impose the minimum bending loads on the shaft.

The cranks of a parallel-twin two-stroke are phased at 180° instead of in line, in order to obtain even firing intervals (Fig. 1c). At first sight it must be thought that, as one piston is going up while the other is going down, the conditions are propitious for obtaining perfect balance.

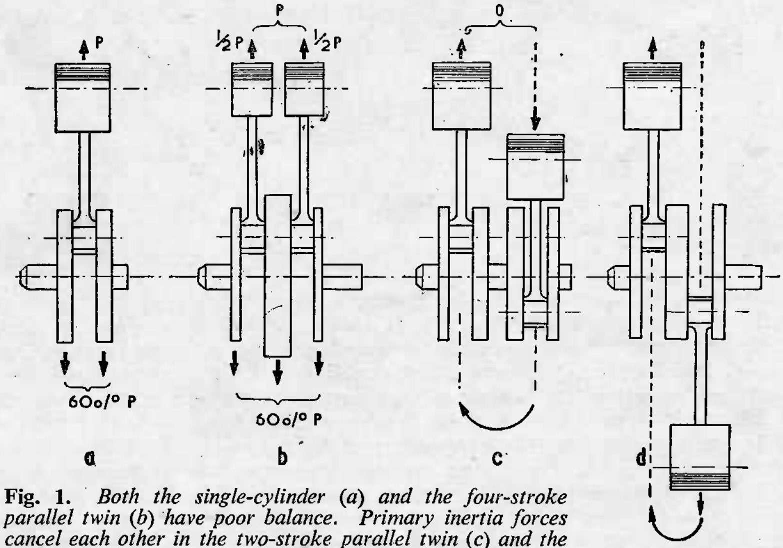


Fig. 1. *Both the single-cylinder (a) and the four-stroke parallel twin (b) have poor balance. Primary inertia forces cancel each other in the two-stroke parallel twin (c) and the horizontal twin (d), but the former has a large rocking couple and the latter a small one.*

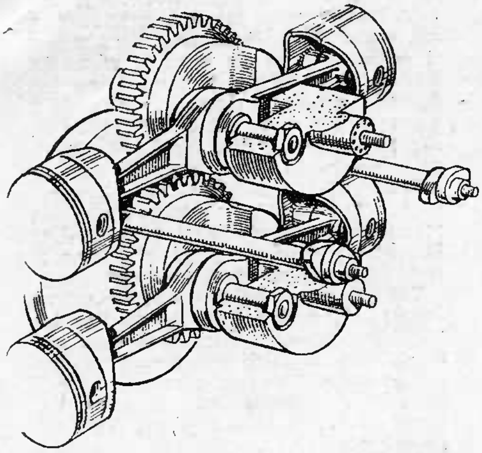
Unfortunately, this is not wholly true. The primary inertia forces from one piston do in fact cancel out the primary forces from the other; but, as the cylinders are necessarily widely spaced in order to provide room for a centre bearing and gas-seals, the two opposing forces combine to form a couple, or turning effort, which tends to rock the engine from side to side. A rough idea of this action can be gained by holding a fixed-wheel pedal cycle up in the air with one hand and smartly twitching the pedals; when released, these will oscillate the machine from side to side due to the rocking couple they exert.

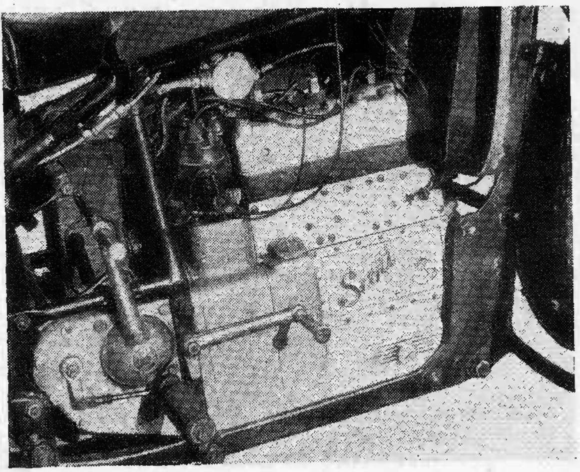
This effect can be eliminated, so far as the crank-pins and cognate parts are concerned, by straightforward counterweighting. But, whatever is done in the way of balancing the pistons, there will always be a rocking couple present, which will be at a maximum in the vertical plane with near-zero balance factor, and at a maximum in the horizontal plane with 100% factor. At any intermediate figure, there will be a tendency to give the crankshaft a kind of conical motion, with its axis describing a figure shaped like a diabolo.

If the engine is reasonably compact, these effects are not serious provided the engine-mounting is designed to cope with them, as it is, to take one excellent example, in the Scott; but even without going to such lengths a duplex cradle frame is essential when the crankshaft lies athwart the machine. If the crankshaft is in line, as in the old Francis-Barnett "Pullman," the rocking couples should be predominantly in the vertical plane, i.e., the plane of greatest stiffness of the frame.

Irrespective of whether the two pistons move in unison or alternately, the secondary harmonic of the primary inertia force acts upwards at t.d.c. and b.d.c., but downwards at the mid-positions. As each secondary force is one-quarter of the primary (see previous article), the net result is a secondary out-of-balance force equal to one-half the primary from one cylinder only, but occurring with a frequency of twice engine speed. Thus the secondary out-of-balance of a 500 c.c. twin at 3,000 r.p.m. is exactly equal in frequency to the primary from a single-cylinder "250" running at 6,000 r.p.m., but has only one-eighth its value, so is not particularly noticeable (if at all) at normal road speeds.

In the horizontally opposed twin, the two-throw crankshaft can easily be balanced in itself, and no additional counterweighting is required, because the motion of one piston is duplicated exactly by the other, but in an opposite sense (Fig. 1d). Thus *all* forces arising from the complex piston acceleration graph cancel each other out within the crankshaft-and-piston assembly,

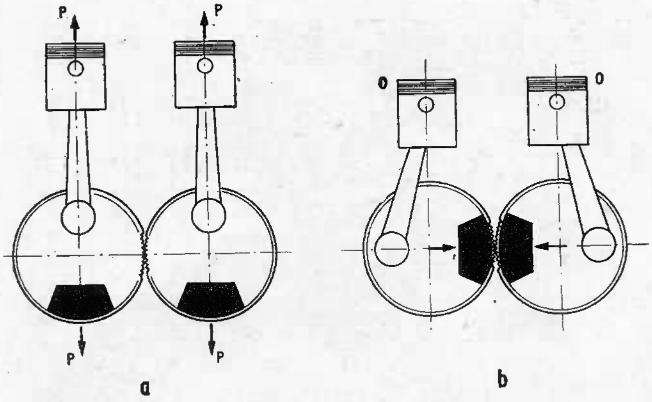




Two rare (but well-balanced) birds. Sketch on the left shows the basic lay-out of the Brough Superior "Golden Dream," with four h.o. pistons coupled to two single-throw geared crankshafts. On the right is the engine room of the 1935 three-cylinder Scott "1,000."

so achieving near-perfect balance and relieving the main bearings of a lot of inertia load as well.

Fig. 2 (*Below*) *On the geared twin, 100% counterweighting gives perfect primary balance (a); centrifugal force from one weight cancels that from the other when no primary inertia force is present (b). Secondary forces not shown.*



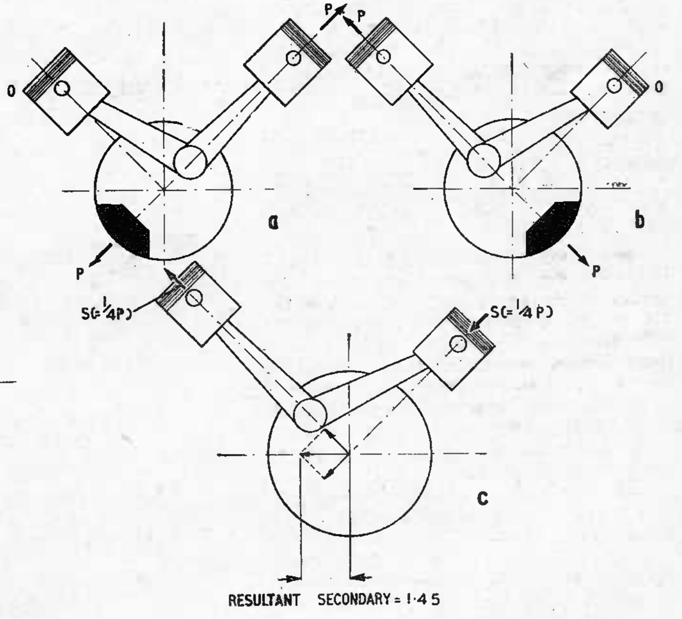


Fig. 3 (*right*) *The 90° V-twin also has perfect primary balance with 100% counterweighting (a-b) and the resultant of the secondary forces acts horizontally (c).*

But for one thing, the balance *would* be perfect. This fly in the ointment is the small rocking couple due to the fact that one cylinder must be offset in relation to the other by the thickness of the centre web plus the width of one big-end. As this distance can be reduced to less than an inch by using narrow roller-bearing big-ends and a thin circular web, the couple is virtually imperceptible, especially in the duplex-frame shaft-drive machines which nowadays utilize this type of prime mover.

Many years ago, Dr. Lanchester propounded the theory that a reciprocating weight could be balanced by two weights rotating in opposite directions, and this system was used for some time in the "Valveless" car, which had two crankshafts geared together and operating pistons which moved in unison.

The idea was resuscitated by Velocettes, 20 years ago, in a pair of experimental machines. The crankshafts of these parallel twins lay fore-and-aft and were coupled by gears of approximately 5-in.-pitch diameter.

This layout enables power to be taken from one crankshaft straight through a gearbox to the final bevel drive, leaving the other crankshaft free to drive the electrical gear or a supercharger without additional gearing. With the shafts rotating in opposite directions, it becomes possible to counterweight each shaft by 100% of the reciprocating weight, because at the mid-points the unwanted horizontal force which makes this amount of counterweighting impracticable with a single is exactly balanced by a similar force from the other shaft. Consequently, the running is extremely smooth, although the effect is achieved at the expense of increasing the average main-bearing loading somewhat.

A secondary out-of-balance force is present, just as in any other parallel twin. Though it is only of minor importance, it could be eliminated entirely by using another of Dr. Lanchester's ideas, and driving a further pair of small wheels at twice engine speed, each being counterweighted to supply a combined force sufficient to balance the secondary vibration.

The V-twin is an interesting form of engine to balance. In the 90° form, perfect primary balancing is obtained by counterweighting to 100% of *one* piston (plus, of course, the small-end). The unwanted centrifugal force from this weight at the 90° positions from No. 1 cylinder exactly cancels out the primary inertia force emanating from No. 2.

But a 90° twin is not an attractive proposition because of its very uneven firing impulses and its large block bulk in big capacities. Consequently, it is usual to reduce the included angle to 50° or 45°.

The pre-war Vincent "Rapide" struck a slightly different note with 47°—an odd sort of angle which was adopted, as so many things are in commercial engineering, because it was expedient to do so, rather than for any theoretical reason. For one thing, it was found that the prototype

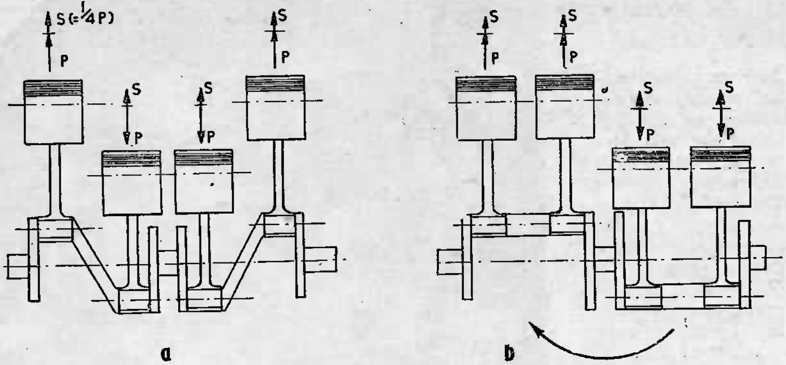


Fig. 4. In the conventional four (a), primaries are balanced and secondaries add up to the primary of one cylinder (P); due to "mirror symmetry," there is no rocking couple. A four with a two-throw crankshaft (b) has the same balance pattern, but a large rocking couple.

crankcase could be machined at little cost by reversing the expensive and accurate jig used to bore the single-cylinder's timing-gear holes; and for another, the valve gear would just, but only just, clear the tubes of a lengthened frame which happened to be on hand.

Not that the exact angle matters much; at anywhere around 50° the balance is about midway between that of a single, which can be half balanced, and that of a 90° twin, which can be fully balanced. In practice, a factor of 35% of the *total* reciprocating weight is found to give a satisfactorily smooth performance, even in sizes up to and over one litre, when mounted in the conventional position.

A secondary vibration is present, but instead of acting vertically it acts horizontally, because it is the resultant of the secondaries arising from the inclined cylinders. It has virtually no effect when the engine is mounted in the conventional position. When the cylinders are placed across the frame, however, this force also acts across the frame and, moreover, at the lower front corner where it is very susceptible to transverse vibration. At 4,000 r.p.m. the maximum value of the force generated in a one-litre twin would be of the order of 250 lb., and the effects of this may account for the number of times this layout has been tried and then abandoned, usually before production has started.

Although it has nothing to do with balance, the fact that in a wide-angle V-twin one piston is moving nearly at its maximum velocity when the other is passing through a dead-centre point, means that the amount of energy stored in both pistons by virtue of their velocities is roughly constant, whereas in any engine where all the pistons reach their extremes of travel simultaneously the stored energy goes from zero to a maximum and back to zero on each stroke. The former therefore needs less flywheel weight because the pistons and rods can be counted as contributing to the total flywheel effect—a characteristic shared by the three- and six-cylinder engines.

The three-cylinder engine is a rather neglected type. This is somewhat surprising, because it possesses perfect balance without the disadvantage of an awkward shape, its worst shortcoming being in the presence of a rocking couple, similar to, though less intense than, that of a 180° twin of equal capacity.

Rocking couples exist in any in-line engine unless the crankshaft has "looking-glass symmetry", i.e., one half of it looks exactly the same as the other half if reflected in a mirror held at the centre. For that reason, there is a rocking couple in a straight three, but not in a straight four with the two end pistons moving 180° out of phase to the centre two—which, of course, is the standard arrangement.

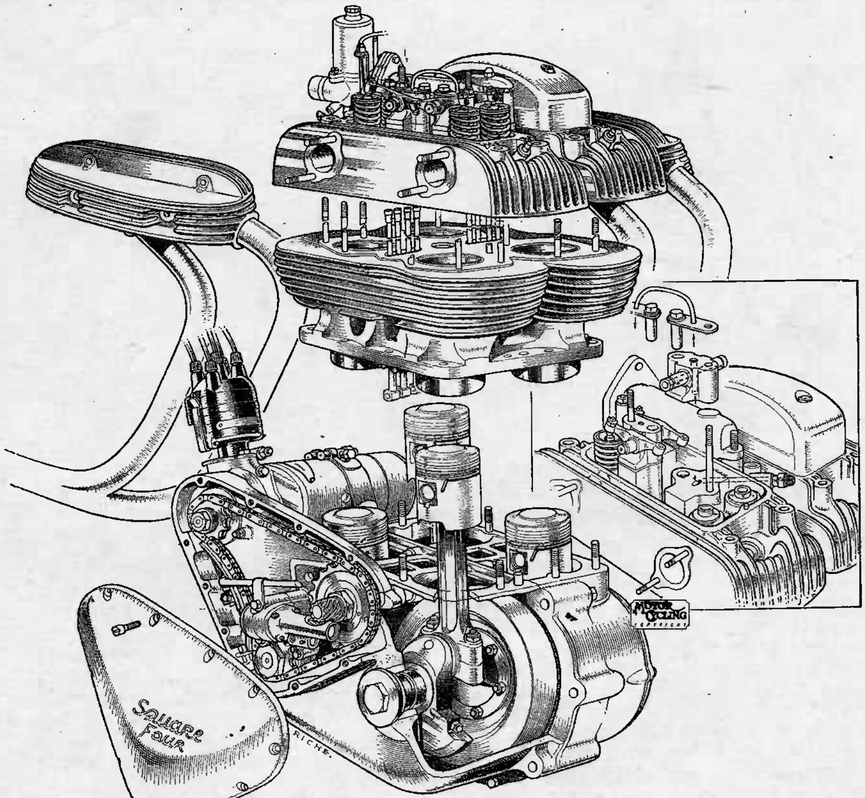
Such an engine is also in perfect primary balance, but as the secondaries from all four pistons act in unison, the total out-of-balance force from this source is considerable, being equal to the primary force from one piston alone. Fortunately, the fact that it occurs at twice engine speed makes its frequency so high that it is well above the natural frequency of most other parts which might vibrate in resonance. Nevertheless, size for size a four is not quite so smooth as a six which is in practically perfect balance and is free from rocking couples.

The "square-four" arrangement, with geared shafts, is equivalent to a straight four bent in the middle, and for balance it is no better and no worse than that type.

The situation is different with the geared four-cylinder engine of the Brough Superior "Golden Dream." Here, each shaft has a single pin, to which two opposed rods are attached so that all four pistons reciprocate as a block. Mechanically, therefore, the layout is similar to that of the Velocette geared twin, with another pair of pistons added, and the primary balance is perfect. But there is a secondary force present, of the same value as that of an equivalent straight four, which might prove an embarrassment with transverse cylinders.

So one can appreciate that where vibrationless running is concerned, "You pays your money and you takes your choice." Any method of improving on the inherently poor balance of a single is accompanied by an increase in cost or complexity, or both, and even then results may not be outstandingly successful unless the installation of the unit is correct for its type.

NEXT WEEK: Valve gearing and layout.



Compactness plus conventional four-cylinder balance: the Ariel "Square Four" engine.