6. Remarks about individual models

Various rotary piston machines are thoroughly examined in this section. They are elaborated with reference to specific inventions which have already become known and the use of the relevant charts is illustrated.

6.1 Reciprocating engagement

Internal axis planetary-rotation machines with reciprocating engagement $(\overline{R})$ have been shown on chart 8 line I columns 1 to 4 (I/1—4). In each of the machines depicted by I/1 the centre of gravity travels in a circular path at constant angular velocity and the piston rotates about its own centre of gravity, while the cylinder also rotates uniformly about its own stationary centre of gravity. There is only a single piston in this machine suitably extended to incorporate a balance weight which ensures that its c. g. coincides with the centre of the crank-pin. It is, of course, far more advantageous when a pair of pistons is arranged one at either end — as illustrated in several configurations on model sheet PLM I (table 11). A particular model — a steam engine — incorporating two such pistons was, in fact, conceived by Parsons, who is perhaps better known for his work on turbines. Indeed, several of these Parsons engines were installed in ships to drive generators and reports stressed their vibration-free performance. The most notable disadvantage is their large overall size relative to the working chamber volume. Steam inlet and outlet are controlled by a single stationary valve disc, the respective ports being opened and closed as the cylinders revolve and sweep past the openings in the disc. This arrangement probably suffered from considerable steam leakage or friction losses in view of the scant knowledge of sealing rotary disc valves available at that time.

Parsons' machine was preceded by Witty's (1811), whose design is shown in the third line of table 11. A trunnion or block and stationary pin (or, as it is sometimes called Scotch yoke) was used in place of a crank. Andrew's steam-rowing machine (1858) table 11 II/3 also belongs to this category. There is no crank in this design, the correct piston movement being ensured by a trochoidal cam plate which moved at a ratio of 1 : 2. An internal combustion engine according to this principle is, for example, the Bucherer engine.

An external-axis reciprocating piston machine, designed by the author in 1929, is shown at I/11 of chart 8. In this, both the piston and the cylinder were given a parallel circular motion. The size of this type of machine relative to its stroke volume is more advantageous than for internal-axis machines with reciprocating engagement. However, the continuously shifting radial strain is less desirable than the centrifugal strain in the revolving cylinders of internal-axis machines.

In the patent specification there was a reference to the possible use of this type of fully balanced mechanism for machine tools. Since 1950 it has become known that the high-speed blanking press produced by 'Lempco Products' incorporates a device of this kind.

6.2 Arctuate engagement $\overline{(A)}$

Single- and planetary-rotation machines with arctuate engagement $\overline{(A)}$ are shown in chart 7 II/1–4, 6, 8 and chart 8 II/5–8, 11. Galloway probably invented the first internal-axis planetary-rotation machine in 1846, see model sheet (chart 1) SIM II 2 (table 12), line 3 No. 2. He used it as a marine steam engine but in the absence of sealing elements its performance was unsatisfactory.

A. Lind suggested in 1914 an internal-axis single-rotation four stroke engine with arctuate engagement, see table 12 II SIM 2, line 1.

Machines with constantly shifting contact points between the engaging components may only be sealed by a special grid arrangement in which the sealing elements contact each other, thereby blocking practically every possible leakage path. Machines with arctuate engagement also feature continuously shifting contact points but it is a peculiarity of the arctuate engagement that every point of the engaging parts circles in a parallel path to all other points; thus sealing may be effected by means of relatively few sealing elements. The sealing elements must protrude slightly out of their grooves in order to seal effectively. These elements subdivide the large curved segments of the meshing component into a number of smaller circular segments but the sealing contact shifts from side to side in sequence.

C. H. Varley invented the paracyclic single-rotation pump in 1919 and fitted a sealing system, as described above, during the development stage. However, the author was obliged to rediscover this type of sealing arrangement in 1947 during his work on single-rotation engines with arctuate-engagement features. This exertion was necessitated by the absence of a comprehensive reference and classification system for rotary piston machines, and single-rotation machines in particular.

In position II/11 of chart 8 is shown, as an example, the planetary-rotation external-axis machine invented by Köpke in 1942.

6.3 Cam engagement $\overline{(C)}$

Internal-axis single- and planetary-rotation machines featuring cam engagement $\overline{(C)}$ and incorporating trochoidal curves are shown in position III/1 and 2 of chart 7 and in positions III/5–8 of chart 8. Single-rotation machines with significant trochoidal curves may be realised in two versions, namely as internal- or external-rotor machines in which the curve generating points and sealing elements are part of the respective inner or outer rotor.

In the case of planetary-rotation machines with trochoidal curves, four variants are possible; two with internal- and two with external-rotors. The curve generating points and sealing elements are part of the inner-rotor in one case and in the other they are part of the outer rotor; in the 3rd and 4th cases they are part of the stationary inner- or outer chamber wall respectively.

Single-rotation machines SIM III/1 (chart 7) were invented by Cooley in 1901 in the form of steam engines. Various attempts have been made since to apply this basic principle to planetary-rotation internal combustion engines, for example, by

Umpleby in 1908 and later by the Renault Company. The attraction of this configuration is undoubtedly the way in which the working chambers are formed almost without parasitic displacement. The Japanese ISUZU company produced in 1963 a SIM type four cycle engine with a relative speed ratio of 3 : 2. This engine featured simple inlet and exhaust ports which were accommodated in the inner rotor. E. Höpner who examined such a configuration in 1954 decided not to pursue this design when he found that the inlet and exhaust gases necessarily pass through the shaft. The ISUZU design resembles, to some extent, known (SIi) engine configurations which have a 2 : 3 speed ratio, its inner rotor possesses the characteristic figure eight trochoidal shape. The outer rotor envelopes the inner rotor as well as accommodating the sealing elements, hence there is an unfavourable relationship between engine bulk and the displacement volume. However if the engine is built as a planetary rotation unit (PLM) part of the power must be transmitted by gearing which is not considered an advantageous expedient. Furthermore, the requirements of adequate port sizes and opening periods of PLM engines cannot be easily satisfied by the configuration. For example, it is possible to accommodate the unavoidable ports — as on two-stroke engines — in the end-covers. Unfortunately, it is impossible to dispense with a precompression phase for much the same reasons as in ordinary reciprocating-piston two-stroke engines — that crankcase compression is utilised to ensure efficient exhaust scavenging and charging of the engine. Provision of adequate port areas leaves only relatively short phases available for the compression and expansion of the gases. According to a study pursued by Ernst Höpner in 1957 rotating disc-valves — one on either side — are essential if the four-stroke cycle is to be accommodated. Engine weight is thereby increased and if the planetary-rotation principle is applied considerably higher bearing loads are obtained due to centrifugal forces. The increase in engine bulk is, of course, also undesirable.

Leaving aside poppet valves, the only other possible timing of port opening is by way of rotary valves driven at an appropriate speed. Earlier internal combustion engines of this type failed partly because of these problems, but in particular because of sealing difficulties.

Since parameters of the NSU-Wankel engine and its sealing system have become known, Renault and others have decided to continue development work on Cooley type planetary-rotation internal combustion engines.

Chart 8 — PLM III/7 and sheet 13 of the classification shows that machines based on the same principles and incorporating identical speed ratios may look very different from each other. If in a machine with a speed ratio of 2 : 1 the rotor is of circular section or if the rotor flanks are made of circular arcs, the rotor may move between the parallel walls of a cylindrical tooth gap. This phenomenon is the same as the locus of a point on the pitch circle of a planet pinion which rolls inside a base circle of twice the diameter of the rolling planet, being a straight line. A diagrammatic sketch of this type of machine is shown in line 2, column 1 of table 13. This machine with its circular rotor and arena shaped bore has a resemblence to the configuration shown in the line above it in the table, except that the latter combines a circular rotor with a trochoidal bore. The difference between the two designs is that whereas there are only two curve generating (contact) points in the design with the trochoidal bore, a multiplicity of contacts, on both sides of the bore, occurs in the design incorporating the straight sided arena shaped bore.

A section through the planetary-rotation pump invented by Moineau (French patent No. 400,508), with screw-type engagement, is similar to the machine illustrated in table 13, second line, first column. However, Ludwig Taverdon of Paris obtained a patent for this type of configuration as long ago as 1878.

Retaining the 2 : 1 speed ratio but introducing two or more circular rotors produces a design similar to the steam engine design patented in 1901 by Franzen and Fahlbeck.

Witte patented a similar diesel engine configuration in 1949. Even if it is possible to master the sealing problems of machines with spherical or rolling cylindrical pistons parallel to the axis of rotation, the resulting machines of this type will not be very desirable. This applies particularly to multi-rotor designs, as unfavourable relationships exist between the displacement volume and the necessary overall bulk of the machine because twice as many cylinders are required as pistons. Only when one double acting piston — first figure table 13 second line — is used is it possible to obtain a favourable displacement/overall bulk ratio.

If, however, this design is converted to a single-rotation machine, for which purpose its piston-rotor will be mounted eccentrically on its shaft while the housing becomes the revolving sealing component, it is possible to re-convert the SIM machine thus obtained, into an easy-to-seal planetary-rotation machine with reciprocating engagement. Accordingly it proved necessary to convert the rotor of the single-rotation machine into an eccentric by mounting on it a planetary-rotation rotor. The resulting configuration is shown in table 11, line 2, column 1.

(To illuminate a little more the multifarious relationships between rotary piston machines in general, it should perhaps be pointed out that this reciprocating-engagement planetary-rotation machine is closely related to the planetary-rotation machine shown in table 19, line 2 column 1 [by Beale]; the power transmitting component of this machine possesses reciprocating-engagement and simultaneously performs the function of a pair of vanes. These vanes revolve in the stationary trochoidal bore with slip-engagement!)

It is possible to derive from the machine shown in table 13, line 2, column 1 a unit with round piston rotors as shown in lines 2 and 3, column 2, which show the rotor in multiple piston form. In addition, it was possible to double the number of generating points and sealing elements, for machines with a speed ratio of 4 : 3 as shown in table 13 and obtain piston rotors of quite different shapes. For the chosen example it was possible to retain the number of teeth and gaps. It is, however, equally possible to reduce the number of teeth and gaps respectively to six each without having to alter the position of the eight sealing elements.

Wallinder and Skoog proposed a planetary-rotation four-stroke cycle engine with a speed ratio of 6 : 5, as shown in table 14, in 1923. Sensaud de Lavaud on the other hand experimented in 1938 with a single-rotation engine, see chart 7 (SIM) III/2, table 15. In its basic form there are only small parasitic cylinder volumes (maximum cylinder volume minus stroke volume) in this design and the ports may be opened and closed by rotor movement. Unfortunately, gas flow requirement demand that parts of the inner rotor are scooped out in order to provide adequate port opening areas and periods, which increase the parasitic volume in each cylinder and, in turn, make it practically impossible to realise present day compression ratios.

It is by no means easy to recognise in every instance whether a particular rotary-piston engine proposal is capable in its simplest form of accomodating the four-stroke cycle. Of the $\overline{(\mathrm{Ci})}$ machines just examined only those with speed ratios of 4:3 and 6:5 etc. may be designed in a form suitable for four-stroke operation. Of the $\overline{(\mathrm{Sli})}$ machines discussed in section 6 and 4 above only those with speed ratios of 2:3 and 4:5 etc. are capable of accommodating the Otto-cycle. Of all other trochoidal configurations, including $\overline{(\mathrm{Ce})}$ and $\overline{(\mathrm{Sle})}$ types, some are quite unsuitable for the application of the four-stroke cycle while others provide additional phases, such as secondary expansion, scavenging or even a supercharging phase, and the engines become special-cycle engines. Only by way of rather complex mechanisms and additional timing devices can these configurations be adapted to the four-stroke cycle.

Various derivations of trochoidal machines are shown on chart8 (PLM) III/5 (table 14). For example, a trochoidal machine having a 2:1 speed ratio was changed into a single-rotation machine with a piston rolling round the bore. Reference should perhaps be made, in this connection, to the straight line locus traced by a point on the periphery of a rolling circle while rolling inside another circle of twice its diameter. The flanks of the housing 'teeth' are, therefore, straight sided. Beneath the trochoidal machine, with a speed ratio 3:2, is a flat vane rotary piston machine as proposed in the early forties by di Blasi for aircraft superchargers. Machines of an entirely different shape were obtained with speed ratios of 4:3 and 5:4 by altering their eccentricity, that is their crank throws.

The bottom line of the diagrammatic sketches shows machines having speed ratios of 2:1, 3:2 and 5:4, their greatly varying chamber shapes being due to doubling the number of generating points and sealing elements (of the models shown above). It will be noted that on machines with speed ratios of 3:2 and 5:4 the inner rotors penetrate their engaging members almost in the fashion of reciprocating motion between practically parallel flanks, which look like cylinders in the sectional sketches.

In 1950 the author made a design study of a 5:4 speed ratio machine using twice the number of curve generating points and tip-seals. In fact it was the development of these radial tip-seals in conjunction with the interlocking axial sealing plates which formed the last but one step towards the development of the sealing system for the first $\overline{(\mathrm{Sli})}$ four-stroke engine with a 2:3 speed ratio.

Internal-axis machines, resembling gear type pumps, as used for heavy oil and other fluids, are shown on the model sheet of single-rotation machines, that is in chart 7 in positions III/3, 4 and 8. This arrangement was also intended to perform as an internal combustion engine. Indeed, it has even been patented for this purpose as exemplified by the two-stroke engine evolved by Brown and Bovery in 1924.

It is possible to devise machines in which a secondary crank rotates about a primary crank (or eccentric); the rotor itself being mounted on the secondary crank. This type of crank upon crank arrangement is prominent on the Doyer or Ruf engines, their rotors revolve at a constant speed which is ensured by suitable gearing. The triangular locii of the respective rotor corners resemble somewhat pointed hypotrochoids due to this double crank arrangement; moreover, the mechanism is fully balanced but the second crank pin is expected to cope with greatly fluctuating centrifugal loads.

The following basic principles apply to machines which feature this crank upon crank (double crank) arrangement.

The respective machine may be either a PLM or PROM machine. If the phasing depends exclusively upon rotor or crank motion, which is controlled by centrally mounted gearing, the respective machine may be either an REM (reciprocating) or PLM (planetary-rotation) machine. Both these machines can be completely balanced.

This double or even treble crank arrangement (crank rotating about a crank pin which is itself revolving about a pin — which also rotates about yet another crank pin) may be applied to rotary or reciprocating-piston machines because the locus of their respective power transmitting rotor (piston) may be practically a circle, a pointed or even looping trochoid or a straight line. Examples of the last mentioned configuration are the machines developed by Pickert or Jones in which the revolving connecting rod, formed by gears, constitute a second crank.

On the same sheet in positions III/9 and 10 are shown internal-axis machines which incorporate short trochoidal curves but no stationary chamber walls because these are formed between the meshing members themselves, in fact between the tooth in one member and the corresponding gap in the other. The actual displacement volume is relatively small and depends upon the tooth profile and proportions. A steam engine design according to this principle was patented in 1903 and 1904 by Jacquet of Strassburg-Königshofen.

Internal-axis internal combustion engines with one power transmitting and one sealing rotor which are enveloped by a common housing, as shown in chart 7 (SIM) III/11, seem to attract the attention of many inventors. It would be equally correct to show one of the widely used external axis gear pumps accommodated in a housing with a similar figure eight bore in place of the example. In this type of single-rotation machine there are no parts which move at variable speed; it was invented in 1636 and is known as the Pappenheim pump. It is interesting that in 1799 Murdock, the congenial collaborator of James Watt, fitted wooden sealing strips in the tip of every tooth and built several of these units as steam engines. Considerable leakages were experienced due to the absence of end-seals and to the inherent inaccuracies of manufacturing methods of the period.

An invention made in England by Jones in 1848, which since 1866 has become known in America as the Roots blower, does not really lend itself to conversion into an engine although it was patented in its oldest form by Holt and Jackson in 1841 as a steam engine. Configurations with inner stationary chamber walls are shown in chart 7 (SIM) III/12 and 14 while chart 7 (SIM) III/15 and 16 show external-axis machines with both internal and external working chamber walls. The design according to chart 7 (SIM) III/16 was invented by Behrens in 1867 and it was executed in the form of pumps and steam engines; in view of the prevailing low pressures it was unnecessary to incorporate any sealing elements: the large areas and close running clearances imposed adequate restrictions.

On the classification sheet for planetary-rotation machines there is a design in position III/11 (chart 8) which incorporates a turning rotor with spherical type pistons — teeth — orbiting in a circular path which engage in similarly circulating bucket type cylinders pivot mounted on a rotating base.

Four external-axis planetary-rotation machines with non-rotating outer chamber walls are shown in chart 8 (SIM) positions III/13 to 16. Not unnaturally the figure eight type bore, so prominent in external-axis single-rotation machines is not required; one of the engaging components assumes the functions of a non-rotating housing which, depending upon the particular design configuration, may — in either an enveloping or penetrating form — become the outer or inner working chamber wall.

When a planetary-rotation machine possesses the figure eight type bore, the bore assumes the functions of a sealing component (containing the working medium) which revolves in unison with the engaging component about the stationary member of the arrangement.

6.4 Slip engagement

Single-rotation configurations of internal-axis slip-engagement machines with trochoidal bore or rotor contours are shown in positions IV/1 and 2 (chart 7) and single rotation versions in positions IV/5–8 (chart 8). In 1935 Fixen described slip-engagement machines with outer curve generating points in his patent specifications. His planetary-rotation $\overline{\text{(Sle)}}$ machines with speed ratios of 3:4 and 4:5 are to be found in chart 8 PLM positions IV/7 (table 16). Fixen designed his machines to have helical slip-engagement.

Single-rotation machines as shown in group SIM position IV/1 (table 7) and a planetary-rotation version with 2:3 speed ratio shown in chart 8 PLM position IV/7 (table 16) were patented by Maillard in 1943 and, indeed, several experimental aero-engine compressors were made according to these principles. This type of configuration is unsuited to the four-stroke cycle because the locations of curve generating points, that is of the sealing elements, do not divide the chambers of any $\overline{\text{(Sle)}}$ designs in the requisite manner.

Slip-engagement machines with inner sealing elements $\overline{\text{(Sli)}}$, as shown in position IV/2 (chart 7) and chart 8 (PLM) IV/5 (table 18), and with speed ratios 1:2 which have been known since 1834 as steam engines were designed by E. Galloway. However, they were mostly manufactured in the form of blowers and compressors. Indeed, Planche (France) is still producing planetary-rotation compressors of this type, albeit with flat spring steel type valves. To convert this type of machine into an internal combustion engine it is, however, necessary to incorporate a rotary valve. Alternatively, it could be made into an engine by providing two units in parallel, one to function as a compressor and the other as the expansion or output device.

Although slip-engagement machines with speed ratios of 1 : 2 and inner sealing elements $\overline{\text{(Sli)}}$ as well as the above mentioned – though not generally known – slip-engagement machines with outer seals $\overline{\text{(Sle)}}$ existed, no attempts were made to evolve other $\overline{\text{(Sli)}}$ machines with different speed ratios. This may be due to the absence of groupings or classifications of rotating piston machines relative to their methods of engagement, and which took into account the location of the curve generating points. It is, however, possible that it was thought that chamber forming $\overline{\text{(Sli)}}$ machines with a speed ratio of 1 : 2 were simply a special epicyclic gearing arrangement offering a particular speed ratio, that is if any thought at all was devoted to the problem.

Reference has already been made in section 6.6, dealing with reciprocating and slip-engagement machines, as to how $\overline{\text{(Sli)}}$ machines with ratios of 2 : 3, 3 : 4 etc. were in fact discovered. The $\overline{\text{(Sle)}}$ type of machine can function as a four-stroke cycle engine; indeed it was the invention of this type of machine which precipitated the sudden and intensive interest of the motor industry in rotary piston internal combustion engines.

Inlet and exhaust ports of $\overline{\text{(Sli)}}$ type four-cycle engines are automatically timed by the movement of the inner rotor. Ports and opening periods may be considerable without having to cut away parts of the rotor. The minimum volume contained in the chamber is small enough to make possible the achievement of any compression ratio as required for modern Otto-cycle engines but the much higher compression ratios demanded by the diesel-cycle necessitate a reduction of the distance between the centres of rotation or the incorporation of a compressor. Unfortunately, a reduction in eccentricity automatically reduces the displacement volume, consequently the overall proportions of diesel engines are necessarily greater than those of equal displacement Otto-cycle engines. The $\overline{\text{(Sli)}}$ type machines with a speed ratio of 3 : 4 shown in table 7 (SIM) IV/2 (table 17) or table 8 (PLM) IV/5 (table 18) represent single- and planetary-rotation engines with additional expansion or charging chambers while machines with 4 : 5 speed ratios may have two inlet and outlet phases or, alternatively, incorporate a charging and a secondary expansion phase. Attention should be drawn to the fact that in $\overline{\text{(Sli)}}$ machines the minimum volume of each chamber increases as the speed ratios go up so that adequate compression ratios can only be achieved by reducing the distance between the centres of rotation – the eccentricity.

6.5 Counter engagement $\overline{\text{(Co)}}$

Counter engagement single-rotation machines are shown in line V of chart 7 and planetary-rotation machines in chart 8. Scheffel (Germany) was granted a patent for the single-rotation machine of chart 7 (SIM) V/10, which incorporates no circumferential chamber walls, while an American patent was granted to H. Walter in 1957 for the gas generator of chart 7 (SIM) V/13. However, it is significant that counter-engagement machines of both arrangements were, in fact, invented a long time before the two examples quoted above.

Machines incorporating the counter-engagement principle show even more clearly than those relying upon the slip-engagement principle that engaging components, which cannot transmit power, may form variable volume working chambers.

6.6 Reciprocating and slip engagement

No rotary piston machine which incorporates reciprocating engagement or possesses reciprocating motion may be transformed from a planetary- into a single-rotation unit. This fact has probably been noted before and may be the reason why planetary-rotation machines which can be converted have, in fact, remained untouched for a very long time. The internal-axis planetary-rotation machines shown on chart 8 in positions VI/5 and 8, which may rely upon reciprocating as well as slip engagement, tend to strengthen this belief because they rely upon the reciprocating engagement principle and cannot, therefore, be converted into single-rotation machines. The units of chart 7 SIM VI/5 and SIM VI/8 have trochoidal rather than circular bore shapes and the housing containing the bore are stationary.

The machine according to SIM VI/5 (see table 19) was invented by Franchot in 1861, furthermore it is often associated with the name of Oldham who patented a paddle wheel in 1826 based upon the same kinematic conception. But, contrary to multi-vane rotating-piston machines, whose power transmitting component — that is the centres of gravity of the vanes — pursue a near circular path at variable velocity, these planetary-rotation machines incorporate straight through vanes whose c.g. move in a circle at twice their actual rotational speed. Woodcock incorporated a pair of straight through vanes, as did Zoller in our time, thereby forming four sickle shaped variable volume chambers. This configuration has been used to a certain extent in the form of superchargers for internal combustion engines and in the form of compressors.

The vanes of older versions of this type of machine were guided by the trochoidal bore. A later design incorporated a sliding block arrangement, also known as 'Scotch Yoke', which was followed by the Zoller principle in which each straight through vane is guided by an inner stationary ring. For this purpose the vanes are suitable shaped — see table 19 line 2. The author preferred at first to link the vane to the crank and later he shaped the vane centre to perform a rolling motion round a stationary pin, an arrangement better suited to deal with the centrifugal forces than the indirect method of allowing the centrifugal forces to increase the main bearing loads — see table 19, line 4.

A comparison may prove instructive. Place next to each other the following illustrations: the slip-engagement $\overline{\text{(Sli)}}$ machine of chart 8 (PLM) IV/5 (table 18), the reciprocating-engagement machines of chart 8 PLM I/1, 2nd place, 1st line (table 11) and the combined slip- and reciprocating-engagement machine of chart 8 PLM VI/5, 3rd line No. 1 (table 19). The relationship of these three machines becomes apparent at once, although only the first of these may also be found on chart 7 SIM IV/2 of the single-rotation design (table 17); the inner rotor of this configuration functions as a sealing component. The second machine cannot be made into a SIM unit on account of the reciprocating motion within the working chamber, neither can the third machine because of the reciprocating motion of the sealing component.

It is perhaps pertinent in this connection to show by way of example how the development of rotary piston machines was hampered by the absence of a sensible classification system capable of providing a comprehensive picture, and of indicating the relationships between different design configurations and of showing up basic principles of design. When the author was working on this comparison he was unaware of the above mentioned $\overline{(\text{SIi})}$ machines which have 1 : 2 speed ratios and a pair of vanes each as they were not included in Reuleaux's 'Theoretical Kinematics' dated 1876 or in the 'History of Rotary Engines and Pumps' — The Engineer 1939 — or in Tänzler's work of 1949 on 'Rotary Piston Pumps and Engines' VDI proceedings volume 91 No. 10. While preparing drawings of various bearing arrangements of straight through vane type power transmitting components, as shown, for example, in the first volume of chart 8 (PLM) VI/5 (table 19), it occurred to him to replace the drum-like inner sealing component by a lens-shaped vane. In this way he reinvented the $\overline{(\text{SIi})}$ type planetary-rotation machine with a speed ratio of 1 : 2 and only one moving part — see chart 8 (PLM) IV/5 (table 18). Because he was unaware at the time of the basic principles of the inconvertibility of planetary-rotation machines with reciprocating-engagement, and of external-axis planetary-rotation machines with arctuate-engagement into single rotation machines, despite the abandoned drum-like sealing component, it was not until 1953 that the thought struck him of letting the outer member rotate. Thus, the inner rotor could revolve round a fixed centre to form a single-rotation machine — see chart 7 (SIM) IV/2 (table 17). It was observed that in this type of single-rotation machine the relationships between the speed of rotation and the number of teeth compared with the meshing action of an annulus gear and an external tooth pinion. A design investigation was therefore commenced in 1954 with a view to evolving machines with other inverse speed ratios, such as 2 : 3, 3 : 4 etc. The $\overline{(\text{SIi})}$ machine, found in this way, with a 2 : 3 speed ratio became the first really practicable rotary-internal combustion engine.

6.7 Slip and counter engagement

Planetary-rotation machines with reciprocating and slip-engagement have been elaborated in part **6.6.** of this book and shown in line VI (chart 8). These machines have, at one and the same time, two different modes of engagement. In addition to the single and planetary rotation machines shown in charts 7 and 8, slip and counter engagement machines appear in line XII.

The single-rotation machines of XII/1 and 4 (chart 7) are attributable to BICERA (British Internal Combustion Engine Research Association), a British research institute supported partly by the state and partly by industry. The design represents experimental engine superchargers of which the sealing components — inner rotors – are in slip engagement with the outer wall of the rotor and in counter engagement with its inner wall. These machines are shown as a planetary-rotation type in chart 8 at XII/9.

An earlier pump developed by Ritz and Schweitzer is shown in XII/8 (chart 7). It may be noted that while the vanes of the BICERA blower are simultaneously in slip and counter engagement, those of the Ritz and Schweitzer pump are either in slip engagement with the inner rotor wall or in counter engagement with the outer rotor wall.

The same mechanism is shown in the form of a single-rotation machine in line XII/6 (chart 8).

6.8 Additional rotation and circular motion

It is possible to create mixed models by giving certain moving components additional rotation or circular motion. It is, for example, possible to give additional rotation to the rotor of the planetary-rotation machine shown in columns 5–8 of chart 8, line II, III or IV, which consists of a rotor which is mounted on a crank pin and a stationary inner or outer chamber wall. Chart 20 indicates diagrammatically the rotor of such a machine in different angular positions and table 21 depicts several machines, one part or the other having been given additional motion.

In general, rotating piston machines should be designed without additional motion unless this movement is essential for the formation of the variable volume working chambers. In special cases it may be expedient to let otherwise stationary components move in order to effect timing of port opening periods or to enable a component to transmit power.

Occasionally inventors have incorporated superimposed movements in their designs without any obvious reason, a trend which seems especially prominent in single and planetary-rotation designs.

When one or more unnecessary additional motion has been superimposed on essential movements, it becomes most difficult to decide the type of basic configuration under examination. The machine in table 20, quoted above, is difficult to analyse although it incorporates only two rotors. Analysis becomes even more difficult if the particular machine has a plurality of moving parts.

It is sometimes essential to recognise superimposed movements because any additional motion given to the c. g. of a component, which has up till then moved at variable velocity, may conceivably give this component uniform velocity. If this has, in fact, been achieved the assumed superimposed motion must be evaluated as a specific movement of the particular design.