

Explorations in the History of Machines and Mechanisms

**THE ROTARY AERO ENGINE FROM
1908 TO 1918**Giuseppe Genchi¹ and Francesco Sorge¹¹ Dipartimento di Ingegneria Chimica, Gestionale, Informatica,
Meccanica – Università degli Studi di Palermo

Abstract: The rotary aero engine is a special type of air-cooled radial engine, where the cylinders are arranged like the spokes of a wheel and turn around the crankshaft. The propeller is connected to the cylinders, while the crankshaft is fixed to the frame. The rotary aero engine, developed in 1908, set new standards of power and light weight within the aircraft industry. It was adopted by many pioneer aviators and widely used to set records of endurance, speed and height. Many aero engine manufacturers produced different models and variants of this type of engine, which was extensively used until the end of the First World War. The latest evolution of the rotary engine was the counter-rotary arrangement, which was devised and designed by the Siemens-Halske company. The distinctive feature of this type of engine was that the engine body (with cylinders and propeller) rotated in one direction while the crankshaft rotated in the opposite one. This result was obtained by using a bevel gear mechanism. However, rotaries were quickly and definitively replaced in 1918 by new kinds of conventional engine, which were developed in the same period by other manufacturers. The main features of rotary and counter-rotary aero engine and the performance limits that caused their decline will be described in this paper. The rotary engine will be compared with the conventional one in terms of power output, specific consumption, weight and inertia loads transferred to the frame.

DEVELOPMENT OF THE ROTARY AERO ENGINE

The power units used in the early aircrafts at the beginning of the XX Century were strictly derived from water-cooled automobile engines or air-cooled motorcycle engines. The water-cooled types were penalized by their heavy weights while the air-cooled were prone to suffer for overheating. The aero engines started their development as a consequence of the increasing specific power demand of aircraft motors. In the early aeronautical era, various kinds of engines were proposed for this purpose by many manufacturers and inventors. Many of these prototypes were of unusual and odd design but were not produced in series or did not have commercial success because of their poor performances. The rotary engine was one of the solutions experimented with success at the beginning of XX Century, a period very rich in innovations and scientific progress. Before its aeronautic application, the rotary principle was already known. It was used in various applications, such as the Millet's motorcycle in 1888 (Fig. 1), which however did not reach success and large diffusion. The rotary aero engine was first introduced into the aircraft industry by the Seguin brothers. They started to develop it by 1906 and then produced their first model, the Gnome 50 HP "Omega", in 1908. This engine is usually considered as the archetypal of the aeronautical rotaries. The 50 HP Gnome, thanks to its peculiar features, granted better performance than its contemporary conventional engines, setting new standards of power and light weight in the aircraft industry. It was adopted by many pioneer aviators and widely used to set records of endurance, speed and height. The "Société des Moteurs Gnome" of the Seguin brothers, was the first and most important rotary aero engine manufacturer of the early rotary era (until about 1912); their engines were also produced under license in many countries. From 1910 others manufacturers, like Le Rhone, Clerget, Bentley, Oberursel and Siemens-Halske, started to design and produce a large number of models and variants. Rotaries were extensively used until the end of the First World War: their success and technical development were as quick as their decline.

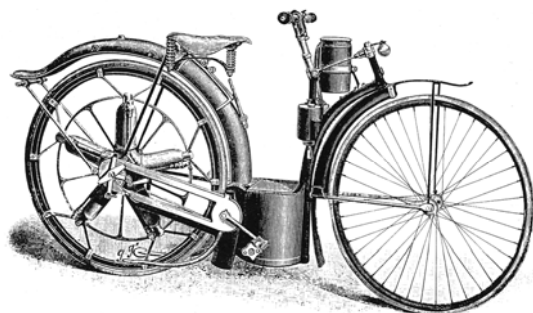


Fig. 1 - 1888 Millet's motorcycle with 5-cylinder rotary engine into rear wheel.

Actually, rotaries were quickly and definitively replaced in 1918 by new kinds of conventional engine with higher performances, which were produced in the same period by other manufacturers. However the rotary engine gave a significant contribution to the development of the aviation industry.

ROTARY AERO ENGINE FEATURES

The rotary aero engine is a special type of air-cooled radial engine, in which the cylinders are arranged like the spokes of a wheel and turn around the crankshaft. The propeller is connected to the cylinders, while the crankshaft is fixed to the frame. In a generic radial engine, both of the rotary and conventional type, a master rod is usually mounted on the crankshaft while a number of slave rods are connected to the master rod. In this arrangement all the rods lie on the same plane with clear advantages with regard the inertia load balancing and the engine length. The success of the aero rotary engine was mainly due to its good cooling capability and its construction lighter than the contemporary aero engines. The first water-cooled aero engines were limited by their heavy weight, whereas the lighter conventional air-cooled ones suffered from a bad or insufficient cooling capability, due to the low aircrafts speed and the scarce cooling efficiency of the cylinder shape. These factors represented an important limit to the performance and reliability of the first aero engines. Studies of those days indicated that a conventional radial engine would have to be given a forward speed of 50 km/h to be cooled to the same degree as a comparable rotary engine running on a test stand.

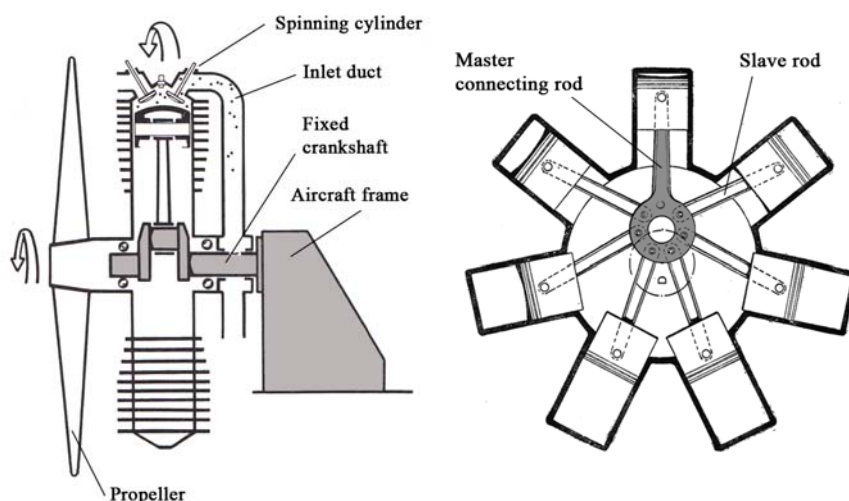


Fig. 2 – Typical rotary engine features.

The efficient cooling of the rotaries resulted from the combination of the wind milling and the propeller slipstream. This also allowed the rotary engines to be realized with a construction lighter than the conventional ones. Rotaries were usually designed with extremely fine section in most components, operating close to the limits of the permissible thermal distortion. At the beginning of the aviation era, the excellent cooling of the engine and the lightweight construction made the rotary engine superior to his contemporaries. However, the rotary design imposed some problems about the admission of the petrol-air mixture to the turning cylinders. In this type of engine, the mixture is drawn through the hollow crankshaft and the carburettor is mounted on the outer end of it. The crankcase is thus utilized as distributor chamber from which the mixture reaches the cylinders in different ways, depending on the particular design. This represents one of the most relevant differences among the various rotary aero engines.

In the early Gnome engines the mixture passes from the crankcase to the combustion chambers through automatic valves in the piston crown. These are of the spring-loaded type like the "atmospheric" valves used in the early motor car engines. When the cylinder pressure falls during the intake stroke, the reduced pressure opens the inlet valve and the mixture is drawn in; as the compression builds up, the inlet valve closes automatically. This type of inlet valve reduces the volumetric efficiency of the engine: it opens later and closes sooner than the proper valve timing. The exhaust valve is of the actuated type and mounted on the cylinder head.

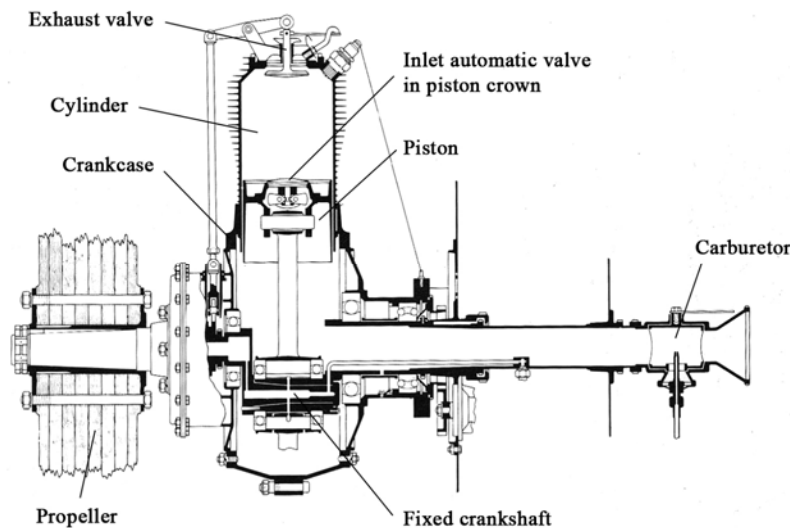


Fig. 3 – Rotary engine Gnome Omega (1908)

In 1913, the Seguin brothers introduced a new design of rotary, the Monosoupape, in which the inlet automatic valve of the piston crown was eliminated. This type of engine has a single overhead actuated valve, with an unusual timing, that is used both to draw fresh air into cylinder and to discharge the exhaust gases. A rich mixture is transferred from the crankcase to the combustion chambers by a row of ports on the bottom of the cylinders. These ports are similar to the ones of a two stroke engine and are uncovered by the piston at the bottom of its stroke. However the Monosoupape, like most rotary engines, operates along a four stroke Otto cycle following the conventional phase sequence. The rich mixture drawn into the cylinder mixes with the fresh air which is already there to form a proper combustible mixture. The engines with this odd feeding system were not less efficient than the contemporary rotaries with conventional design. The Monosoupape engines in fact were used by the Allied air forces throughout the First World War. This kind of rotary was introduced in order to replace the crown inlet valve, which frequently gave some trouble caused by a dangerous backfire on the crankcase. The new design of the Gnome engine exhibited fewer parts, reduced weight, better reliability and about the same power.

The rotary engines produced by other manufacturers, such as Le Rhone, Clerget, Oberursel and Bentley, usually had a more conventional valve system in which the inlet manifolds (one per cylinder) were fitted radially out of the crankcase and reached each cylinder head. The mixture admission and the exhaust gas discharge were controlled by pushrod actuated overhead valves, usually two per cylinder.

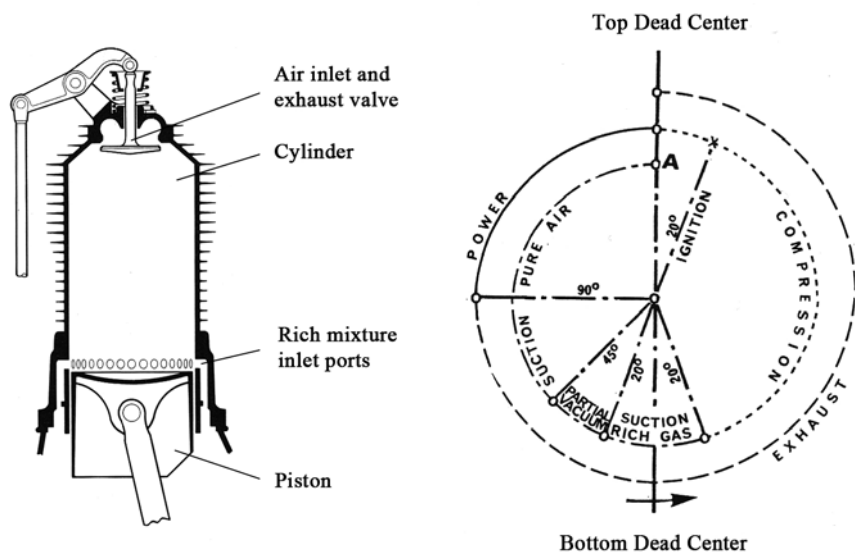


Fig. 4 - Gnome Monosoupape cylinder and its engine cycle features.

THE COUNTER-ROTARY AERO ENGINE

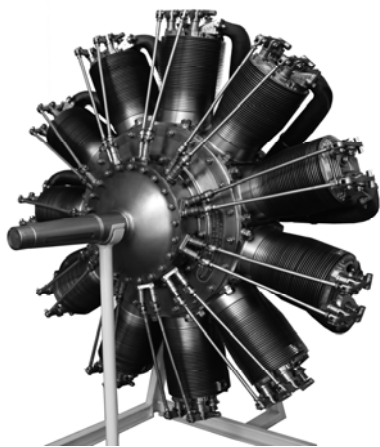
The latest evolution of the rotary engine was the counter-rotary type, first and only designed in 1914 by Siemens-Halske, a brand of Siemens AG. The distinctive feature of this type of engine was that the crankcase (including cylinders and propeller) rotated in the one direction while the crankshaft rotated in the opposite one. This effect was obtained by using a bevel gear mechanism with speed ratio -1.

The best counter-rotary engine was the Siemens-Halske Sh.III, which featured the considerable power output of 200 HP with a power-to-weight ratio of about 1 HP/kg. This engine, which was produced in considerable quantities (about 1200 exemplars until 1918), was fitted to different aircrafts including the Siemens-Schuckert D.III and D.IV. These aircrafts featured an exceptional rate of climb thanks to the performance of their Sh.III engine, and have been considered as the best German fighters produced during the First World War.

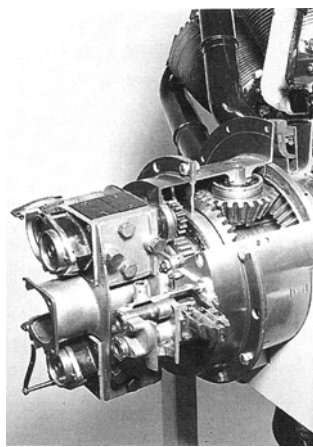
The counter-rotary design was devised in order to reduce the propeller speed with the purpose of improving its efficiency without reducing the power output. Improvements in performance to this point in time had been achieved by increasing engine speed, with systems immediately preceding the counter-rotary design, featuring maximum speeds of about 1400 rpm. Nevertheless, this caused some problem regarding the efficiency of the fixed-pitch wooden propellers in use in that period. A reduction gear mechanism had been introduced before the propeller in the contemporary conventional engines but it was very difficult to arrange a similar mechanism in the rotaries. In a Sh.III engine, the fine counter-rotary design allows both the propeller to run efficiently in its usual range of 900-1000 rpm, and the engine to produce a power output corresponding to a speed of about 2000 rpm of the simple rotary, i.e. twice that of the propeller. In fact, other engine parameters being equal, the power output is dependent on the frequency of the thermodynamic cycle: in a counter-rotary, thanks to the bevel gear mechanism, this corresponds to the sum of the absolute values of both the crankcase speed (cylinders plus propeller) and that of the crankshaft. The reduction of the cylinder speed gave two other advantages: a significant decrease of the windage losses from the spinning cylinders and a moderate reduction of the engine gyroscopic effect for the benefit of the aircraft manoeuvrability, due also to the counter rotating masses of the crankshaft together with its balance weights and the connecting rods. Unlike the early rotary engines, the 200 HP power output of the Sh.III ensured an aircraft speed sufficient for a correct cooling of the cylinders, which ran at "only" 1000 rpm, rather than at the usual 1300-1400 rpm of the contemporary rotaries.

On the other hand, the Siemens-Halske Sh.III, such as all the other German rotaries, suffered for the use of poor quality lubricant oil. In that period, the castor oil was the best lubricant available, clearly superior to the contemporary mineral oils, and it was widely used for this reason on the rotaries, whose fine construction

was extremely sensitive to the lubricant quality. In Germany, there were insufficient castor oil supplies and so the use of mineral oils limited the operating life of the early Sh.III engines to about ten hours before the pistons began to seize.



Sh.IIIa of the Historic Museum of Engines and Mecanisms of the University of Palermo



Sh.III of the Science Museum of London.

Fig. 5 – Counter-rotary engine Siemens Sh.IIIa, with detailed views of bevel gears.

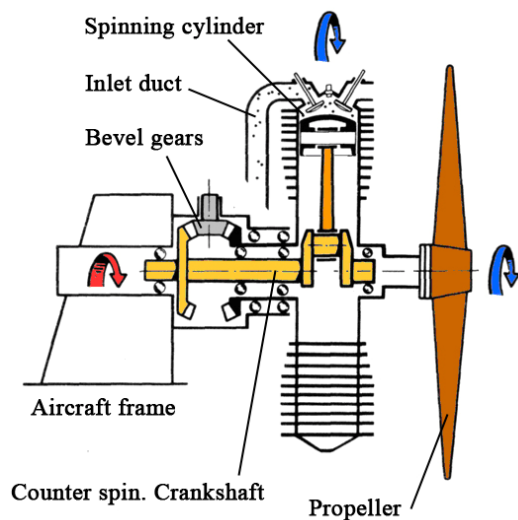


Fig. 6 - Counter-rotary engine Sh.IIIa features.

THE LIMITS OF THE ROTARY AERO ENGINE

The peculiar features that granted the rotary engine success were the same that caused its decline. The cylinders' spinning gave a superior cooling effect and permitted the engine lighter construction than other conventional air-cooled or water-cooled earlier engines. Nonetheless, during the short life of this kind of engine, it was experienced that the peculiar characteristics themselves of the design implied significant limits to some of the main factors on which the engine performance depends: volumetric efficiency, engine speed and displacement.

In a rotary engine, the mixture passes through the hollow crankshaft, emerges into the crankcase and at least arrives into the combustion chambers through long inlet ducts, or else transfer ports as in the Gnome Monosoupape engines. The intake path is very long and extremely tortuous and this implies remarkable pressure drops with consequent significant reduction of the volumetric efficiency, that is of the power output. By comparison, the more advanced conventional engines realized near the end of the War are equipped with simple and direct inlet ducts. Therefore, the use of odd inlet valve system, such as the automatic valves on the piston crown or the transfer ports for the intake of rich mixtures, implies a certain reduction of the number of parts and of the weight but causes a further decrease in the volumetric efficiency with respect to the conventional valve system operation. In Table I, which reports the specific power, the displacement and the brake specific fuel consumption of several engines, the negative effect of the poor volumetric efficiency and of the significant inlet pressure drop typical of the rotary design appears evident with respect to the conventional engine. In synthesis, the poor volumetric efficiency was a peculiar trouble of the rotary design which implied an irremediable disadvantage for the improvement of its performance.

The mechanical stressing of the materials due to the centrifugal loads did not represent an important problem for the rotary engine, mainly because the maximum engine speed was limited at the time by the standard use of fixed-pitch wooden propellers. As the crankcase speed increased (together with the propeller speed), the airscrew thrust efficiency decreased. This trouble was solved on the conventional engine by mounting a reduction gear mechanism before the propeller, whereas the only effective solution adopted for the rotaries was the counter-rotary design. For this reason the maximum engine speed of all rotaries was about 1400 rpm with the exception of the Siemens Halske Sh.III, while the other types could rotate up to 2000 rpm on approaching the end of the War.

The mentioned technical limitations led many manufacturers to improve the engine performance by increasing the displacement. However this solution implied to increase the sizes, the mass and the gyroscopic effect, with negative consequences on the aircraft manoeuvrability. Furthermore the bore increase of an air-cooled thin-wall cylinder implied some thermal distortion trouble: it was caused by the cooling flow rate differences between the front and the rear part of each cylinder.

Finally, the power output of the high-performance later rotaries implied a significant increase of the aircraft speed, so that the cooling effect of the spinning cylinders began to be considered as just negative due to its related windage losses. On the other hand, the cooling troubles of the early air-cooled aero engines was also faced in other ways, e.g. by improving the cylinder shape or by using materials with high heat transfer coefficients, such as aluminium alloys.

The conventional aero engines (specially of the water cooled types) that were developed in the same period by important manufacturers such as Daimler, BMW, Rolls Royce, Salmson, Hispano-Suiza and Fiat, did not suffer for the rotary limitations and so bridged the early performance gap. Table I gives a synthetic comparative analysis among some important rotaries and some other contemporary conventional engines. The most significant parameters of the aero engine performances are taken into consideration: the brake specific fuel consumption, which is an engine efficiency indicator, the brake mean effective pressure (BMEP), which is proportional to the torque-to-displacement ratio, the power-to-displacement ratio and the power-to-weight ratio.

Engine Type Year	Displ. [litres]	Weight [kg]	Power [HP] (rpm)	Brake specific fuel cons. [g/(HP*h)]	BMEP [bar]	Power to displ. ratio [HP/litres]	Power to weight ratio [HP/kg]
Gnome Omega* 7-cylinder rotary 1908	7.98	75	50 (1200)	388	ca. 4	6.3	0.67
Clerget 11 EB 11-cylinder rotary 1916	23.60	230	200 (1300)	300	5.65	8.5	0.87
Bentley BR2 9-cylinder rotary 1918	24.92	226	230 (1300)	286	6.34	9.2	1.02
Siemens Sh.IIIa 11-cyl. count.-rot. 1918	18.60	198	200 (1000**)	270	5.52	10.8	1.01
Daimler D.IVa 6 in-line cyl.*** 1916-1918	21.70	405	260 (1450)	230	ca. 8.0	12.0	0.64
Hispano-Suiza 8FB 8-cyl. V 90° **** 1917-1918	18.48	275	300 (1800)	230	ca. 8.0	16.2	1.09

Table I - Performance comparison among rotary and conventional engines.

*: First aero rotary engine. **: Propeller speed. ***: Water-cooled engine.

ROTARY ENGINE DYNAMICS

The rotating crankcase arrangement turns out to be beneficial to the overall engine dynamics and this aspect may have probably influenced its temporary success. On the one hand, apart from the potentiality of halving the angular speed for fixed power level, the counter-rotary architecture offers the advantage of improving the aircraft manoeuvrability due to a sort of compensation of the angular momentum between the contra-rotating parts. On the other hand, both rotating-crankcase schemes may be shown to produce a non-negligible lowering of the inertia forces acting on the frame. Such forces can be generally scaled by the product of three factors, the motor mass, the square of the angular speed and some reference motor length. Therefore, for geometrically similar engines, the inertia force amplitude is proportional to $N^2 V^{4/3}$, where N is the rev number per unit time and V the volume, whilst the inertia torque amplitude is proportional to $N^2 V^{5/3}$. Wishing to compare the radial engines on the basis of the same power and the same sizes, the angular speed of the counter-rotating engine must be one half of the other two and its inertia forces and moments must be multiplied by a factor $1/2^2$ for the comparison.

The inertia force system of the counter-rotary engine is different from the fixed-crank and the conventional fixed-crankcase arrangements. As the outer cylinder body is perfectly balanced and symmetric with respect to the axis of rotation, the counter-rotary dynamical behaviour would seem to be similar to the rotating crank configuration, the main differences arising from the double frequency of the force reciprocation with respect to the output shaft. As a matter of fact, comparing the three engine types in the absence of counterweights, the fixed crank arrangement would generally exhibit better balancing conditions because of the suppression of the predominating centrifugal effect of the crank rotation, whereas the reciprocating forces arising in the rods and the pistons balance each other approximately due to the star shaped engine structure. Nevertheless, the centrifugal forces associated with the crank rotation may be efficiently balanced by mounting suitable counterweights on the crankshaft back, which restore the rotating crank competitiveness. Actually the counter rotary engine ShIII is equipped with two proper balancing masses on the crankshaft.

Figure 7 shows a scheme of the rods and Table II summarizes the inertia force system, which was derived by conventional procedures (e. g. see [6]). The introduction of the auxiliary dummy coefficients d_c , d_i and d_o permits applying the compact formulation of Table II to all radial engines. The rod obliquity angles φ vary during the cycle and are to be calculated by proper closure equations of the triangle OA_0B_0 and the quadrilateral OA_0AB , as shown in Fig. 7.

The moments of the inertia forces with respect to the engine axis through O are resisted in part by the crankcase and in part by the crank. The fraction loading the crankcase can be calculated once the mutual forces exchanged between the pistons and the cylinders orthogonally to their contact walls are found. This can be done

for the slave rods ($j = 1$ to 10) by simply imposing the rotational equilibrium with respect to the crankpins A . With regard to the master rod, after calculating the mutual forces between slave and master rods through the crankpins A by the translational equilibrium of each slave rod, the rotational equilibrium around A_0 yields the reaction force exchanged between the master rod and the master cylinder. Once the inertia torque on the cylinder body is calculated, the torque fraction loading the crank is then obtainable by difference. In the engine configuration with just one rotating part, either the crank or the crankcase, the described calculation gives the inertia torque on the frame and the residual torque fraction applied to the propeller shaft, which merges in practice with the driving torque but does not affect its value on the average. In the counter-rotary engine on the contrary, the crankcase torque fraction is transferred to the propeller directly, while the crank torque is transferred to the bevel gearing set. As the crank and crankcase speeds are equal and opposite, the latter torque fraction is balanced by an equal reaction moment applied by the opposite bevel gearwheel, which is connected in turn to the output shaft. Therefore, the moment $2(M_{O,tot.} - M_{O,crankcase})$ is applied to the aircraft frame, while the sum $M_{O,crankcase} + (M_{O,crankcase} - M_{O,tot.})$ merges with the driving torque applied to the propeller, without affecting its average value of course during one complete cycle.

Figure 8 shows the diagrams of the inertia forces and moments for the three examined configurations. They were traced in the hypothesis of perfect balancing of the "centrifugal" forces by means of suitable counterweights, i. e. by putting $d_i = 0$ identically in the formulae of Table II. Moreover, as an equivalence criterion between the counter rotary and the simply rotary configurations, it is assumed that the angular speed of the latter ones is twice the former, in the hypothesis of equal sizes and equal power of the three engines. As the inertia forces and moments are scaled by $m_s l_0 \omega^2$ and $m_s l_0^2 \omega^2$ respectively, where ω refers to the counter-rotary engine, a factor 4 arises in the scaling process of the two other engines.

The doubling of the inertia reciprocation feature is clearly observable in the

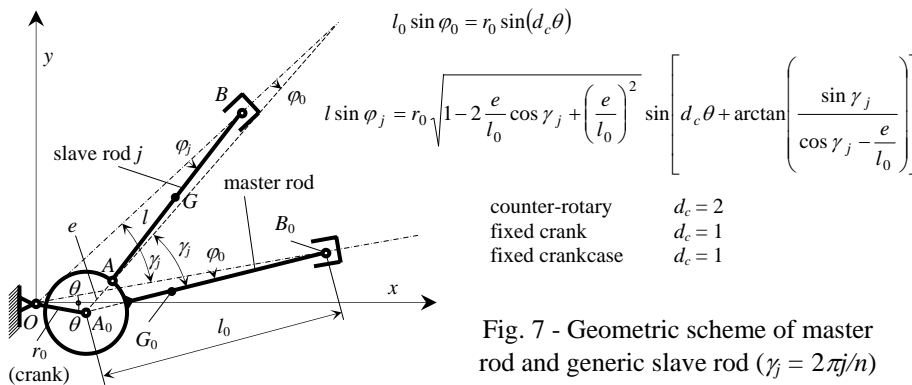


Fig. 7 - Geometric scheme of master rod and generic slave rod ($\gamma_j = 2\pi j/n$)

counter-rotating case, together with a common characteristic of the three arrangements: the x component of the resultant inertia force is symmetrical with respect to the configurations $\theta = 0$ and $\theta = \pi$ (crank and master rod aligned), while the y component and the moments are anti-symmetric. Numerical tests with unbalanced "centrifugal" forces may be found to yield much higher levels of F_x and F_y for the contra-rotating and fixed-crankcase arrangements, due to the nearly stellar configuration of the reciprocating inertia forces and the parallelism of the centrifugal ones. Nonetheless, considering properly counter-weighted cranks, the fixed-crank and counter-rotary configurations appear to produce the lowest average levels of the inertia forces, which implies smoother vibratory conditions and may have been perhaps one of the reasons why these solutions had a rather larger success during the early decades of the 20th century. The inertia torque on the frame is lowest in the fixed crank arrangement and highest in the fixed crankcase one, the counter-rotating case taking place in an intermediate position. In short, the rotating cylinder configuration was no doubt advantageous with regard to the dynamics of the engine, whose balancing requirements did not certainly impose any development limitation.

$$\frac{F_{x,j}}{\omega^2} = (m_{r,j} + m_p) \left\{ r_0 d_i \cos \theta + e \operatorname{sgn}(j) \left[\left(d_o + \frac{\dot{\varphi}_0}{\omega} \right)^2 \cos(\theta d_o + \varphi_0 + \gamma_j) + \left(\frac{\ddot{\varphi}_0}{\omega} \right)^2 \sin(\theta d_o + \varphi_0 + \gamma_j) \right] \right\} +$$

$$(m_{r,j} l_{G,j} + m_p l_j) \left[\left(d_o + \frac{\dot{\varphi}_j}{\omega} \right)^2 \cos(\theta d_o + \varphi_j + \gamma_j) + \left(\frac{\ddot{\varphi}_j}{\omega} \right)^2 \sin(\theta d_o + \varphi_j + \gamma_j) \right]$$

$$\frac{F_{y,j}}{\omega^2} = (m_{r,j} + m_p) \left\{ -r_0 d_i \sin \theta + e \operatorname{sgn}(j) \left[\left(d_o + \frac{\dot{\varphi}_0}{\omega} \right)^2 \sin(\theta d_o + \varphi_0 + \gamma_j) - \left(\frac{\ddot{\varphi}_0}{\omega} \right)^2 \cos(\theta d_o + \varphi_0 + \gamma_j) \right] \right\} +$$

$$(m_{r,j} l_{G,j} + m_p l_j) \left[\left(d_o + \frac{\dot{\varphi}_j}{\omega} \right)^2 \sin(\theta d_o + \varphi_j + \gamma_j) - \left(\frac{\ddot{\varphi}_j}{\omega} \right)^2 \cos(\theta d_o + \varphi_j + \gamma_j) \right]$$

$$M_{O,j} = -I_{G,j} \ddot{\varphi}_j - F_{(r)x,j} y_{G,j} + F_{(r)y,j} x_{G,j} - F_{(p)x,j} y_{B,j} + F_{(p)y,j} x_{B,j}$$

Table II – Inertia force system

Notation:

$\omega = \dot{\theta}$, angular speed of propeller shaft (dots indicate time derivatives);

$\gamma_j = 2\pi j/n$, angle between generic rod j and master rod ($j = 0 \dots n-1$, $j = 0$ refers to master rod and n is the number of cylinder, e. g. $n = 11$ for Sh.III);

m_p , piston mass;

$m_{r,j}$, $I_{G,j}$, l_j and $l_{G,j}$, masses, barycentric moments of inertia, total length and barycentric distances from crankpins of rods ($m_{r,j} = m_r$, $I_{G,j} = I_G$, $l_j = l$ and $l_{G,j} = l_G$ for $j > 0$; $m_{r,j} = m_{r0}$, $I_{G,j} = I_{G0}$, $l_j = l_0$ and $l_{G,j} = l_{G0}$ for $j = 0$);

subscripts (r) and (p) refer to the rods and the pistons separately;

$d_i = \operatorname{sgn}|\omega_{\text{crank}}|$ and $d_o = \operatorname{sgn}|\omega_{\text{crankcase}}|$ are unitary dummy coefficients that vanish for fixed inner crank and fixed outer crankcase respectively.

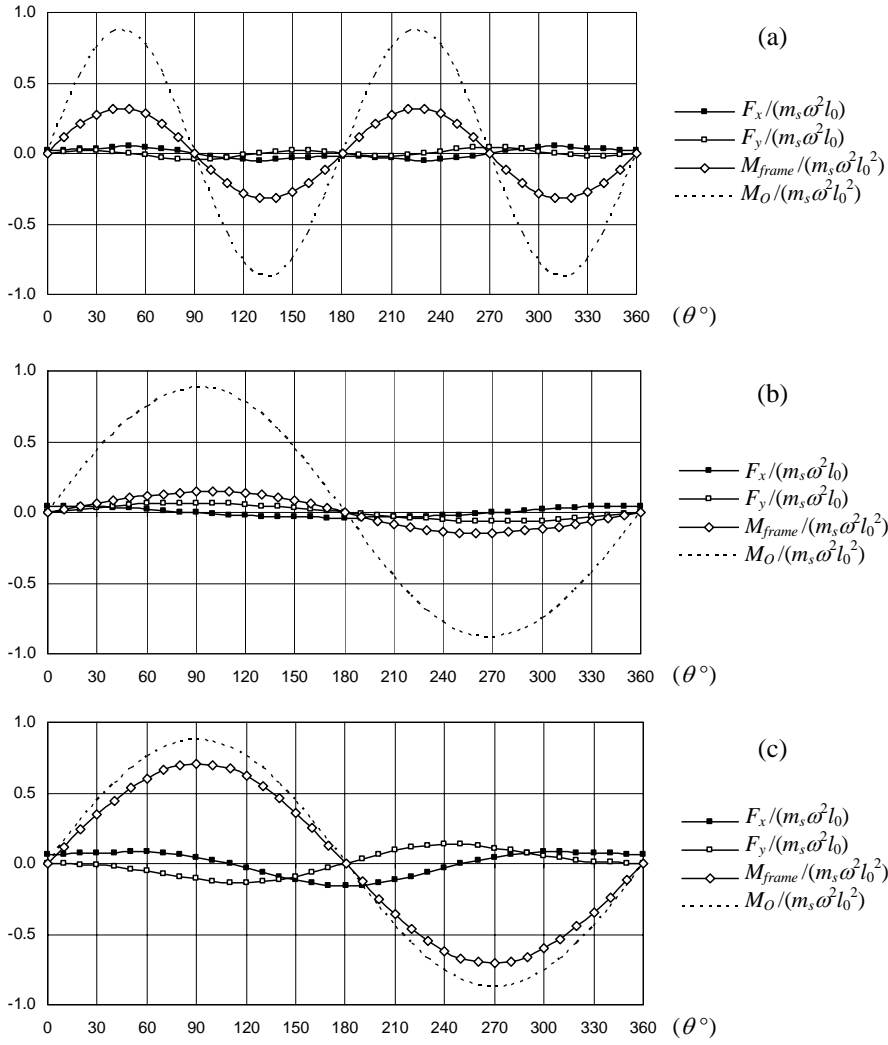


Fig. 8 - Inertia forces and moments. (a) counter-rotary; (b) fixed-crank; (c) fixed-crankcase. Equal motor sizes, $\omega =$ counter-rotary engine speed ($\omega_{(b)} = \omega_{(c)} = 2\omega$). Massive and geometrical characteristics assumed by previous figures and engine plans.

CONCLUSION

The rotary aero engine set new standards of power and light weight in the field of aircraft industry from its dawn in 1908. During the ten years of its development it gave an important contribution to the early aeronautic industry. It was adopted by many pioneer aviators and widely used to set records of endurance, speed and height. The peculiar features granting the early rotary engine success were the high power output and the good cooling effect on the engine cylinders. Moreover, its vibratory behavior appeared quite smooth. But these properties were obtained thanks to the particular rotary design that implied, as experienced during its development, significant limits on the improvement of the engine performance. The major limitations were the low volumetric efficiency and the difficulties to enhance power by increasing displacement and speed engine. The conventional aero engines (specially the water-cooled types) were developed in the same period by important manufacturers such as Daimler, Rolls Royce and Hispano-Suiza, and from 1918 these engines were able to provide equal or better performances than rotaries. Furthermore these ones, unlike the rotaries, showed considerable improvement possibilities, which were realized in the following years. To conclude, it is possible to say that from the end of the First World War, rotaries were quickly and definitively replaced by the conventional engines which, after evolving in the famous high-power piston engines of the Second World War, were widely substituted in a very short time in the aeronautic industry by the turbojets about 30 years later.

References:

- [1] Filippi, F. (1983), *Dall'elica al getto*, Associazione Industriali Metallurgici Affini, Edizioni EDA, Torino (I).
- [2] Giger, H. (1986), *Kolben-Flugmotoren*, Motorbuch Verlag, Stuttgart (D).
- [3] Nahum, A. (1987), *The rotary aero engine*, HMSO Books, London (UK).
- [4] Gunston, B. (2006), *Development of piston aero engines*, Patrick Stephens Limited, Haynes Publishing, Sparkford (UK).
- [5] Von Gersdorff, K., Schubert, H., and Hebert, S. (2007), *Flugmotoren und Strahltriebwerke*, Bernard und Graefe Verlag, Bonn (D).
- [6] Biezeno, C.B., and Grammel R. (1954), *Engineering Dynamics*, Blackie & Sons Lt., London (UK).