Synchronisation systems

*This is based on **Flying Guns: World War I** and **Flying Guns: World War II** by Anthony G Williams and Emmanuel Gustin*

In the era of propeller-driven fighter planes from WW1 to the end of WW2, designers had problems with installing the gun armament. The optimum place for the guns was close to the aircraft's centreline, in order to avoid the problems caused by the alternative of mounting guns in the wings. This could adversely affect the aircraft's agility and resulted in the need to "harmonise" the guns to concentrate their fire at some specified distance(s) – which led to a more dispersed fire at other ranges. Also, in WWI it was desirable for the guns to be within reach of the pilot so he could clear the frequent jams caused mainly by inconsistent ammunition.

However, the optimum configuration for a single-engined fighter in both world wars was found to be with the engine and propeller mounted in front of the pilot. The propeller disc therefore blocked the line of fire from centrally-mounted guns. Various solutions to this were tried, the most popular initially being to mount the gun(s) on the top wing of a biplane, access to the guns being eventually facilitated by a device to pull them down towards the cockpit. Another solution was to fit the propeller blades with steel wedges to deflect bullets – but this didn't do much for the aerodynamic efficiency of the propeller. The most desperate remedy was to accept that the occasional bullet would strike a blade, and bind the blade with tape to try to persuade it to hold together for the duration of the mission. The ultimate solution, however, was synchronisation: timing the firing of the guns so that the bullets passed between the propeller blades as they rotated.

World War I

The first design for a device to synchronise the firing of the gun or guns with the rotation of the propeller was patented by Franz Schneider, although Blériot was also working in this field. However, his first patent in July 1913 was more precisely an interrupter rather than a synchronising gear; i.e., the mechanism prevented the gun from firing while a propeller blade was in front, instead of positively firing it when the line of fire was clear. This latter approach was the method eventually adopted, although the term "interrupter gear" remained in popular but inaccurate use for some time after. It should be noted that a synchronising gear effectively turned the machine gun into a semi-automatic weapon, as it only fired one shot for each firing impulse received. It seems that Schneider had thought of this method as well, so should not be denied the credit. His patent envisaged a flexible synchronised gun, albeit with a limited range of movement.

This was followed in April 1914 by the Frenchman Raymond Saulnier's patent mechanism which used an oscillating rod to fire the gun (a flexible link was also proposed). More significantly, Saulnier also built the first practical synchronising gear at this time, but suffered from applying this to a Hotchkiss which was inherently unsuitable for synchronisation. Obviously discouraged by the results, Saulnier invented the steel deflector wedges as a simpler solution.

The Edwards brothers patented a synchronisation gear in Britain in the summer of 1914, but when they approached the RFC with it, they were told that the service did not have any money for that kind of development.

The first use of synchronising gear in aerial warfare did not occur until 1915, following the capture by the Germans in April of that year of a French aircraft using the deflector type of mechanism. The *Idflieg* (*Inspektion der Fliegertruppen*) sought a comparable system and Anthony Fokker (who, although Dutch, had a factory in Schwerin, Germany) produced the first example of an aircraft fitted with a synchronising gear in May 1915. It seems likely that the *Gestänge-Steuerung* gear was actually designed by Heinrich Lübbe, an employee of Fokker's, based on Saulnier's patent. Initial versions used rigid connecting push rods to fire the gun but these proved troublesome (they were sensitive to temperature changes and would contract in the cold, preventing operation of the trigger) so flexible drive shafts were employed in later designs. The Fokker system remained predominant in Germany but other synchronisation gears were also used, such as the Albatros-Hedtke fitted to all Albatros D aircraft until August 1917 when it was replaced by an improved version, the Semmler, fitted to the D.V.

At first, Allied efforts were hampered by the preference for using the Lewis and Hotchkiss *Aviation* guns, so much lighter than the Vickers-Maxim type. However, the mechanism of these guns was fundamentally unsuited to synchronisation as there was no positive firing pin release; they fired from an open bolt, the primer being struck automatically as the breech closed. On receiving the firing signal, the bolt was released to move forwards under spring pressure, pushing a cartridge from the ammunition feed and into the chamber, and then locking the bolt before the gun could fire. The time delay between the pilot pressing the firing button and the first shot being fired was far too long for the accurate timing required.

For effective synchronisation the time between the firing signal and the moment when the projectile leaves the barrel (the lock time) is crucial. Because the propeller rotates over an important angle during this interval, this time needs to be accurately controlled. It also needs to be as short as possible, because the rotation speed of the propeller itself is not constant but dependent on engine rpm, and the longer the lock time, the greater the variation in propeller travel. Little progress with synchronisation was made until the Vickers-Maxim guns, which happened to have a positive striker release and fired from a closed bolt, was modified for the purpose; the lock time was much shorter, about one-twelfth that of the open-bolt types.

The British, stimulated by the success of the synchroniser-equipped German fighters, started to develop their own gear in Autumn 1915. First in the field was the Vickers-Challenger, introduced in March 1916 (the patent was applied for in January, well before the first Fokker with synchronisation gear was captured), but this experienced reliability problems and was replaced first by the Scarff-Dybovsky (a favourite of the RNAS), Sopwith-Kauper and other less common systems until the Constantinesco-Colley (or CC) hydrosonic gear entered service and rapidly became the standard thereafter.

Earlier systems had all used a mechanical linkage driven by a cam on the engine crankshaft (or in some cases the camshaft). The longer the distance from the gun to the propeller over which the linkages had to operate, the more problems there were with backlash, wear, heating and cooling. Very careful maintenance was required to keep them functioning properly, and malfunctions were common. The use in the CC gear of hydraulic pipes to transmit the pulses, or percussive wave transmissions, permitted more precise control and thereby the highest rate of fire, helped by the fact that two firing signals were sent per propeller revolution. It should be emphasised that this was not a conventional hydraulic system; the liquid in the pipes did not move, but merely transmitted the sonic pulses at very high speed, the ingenious invention of George Constantinesco. It was theoretically capable of sending 2,400 firing impulses per minute to a two-gun installation, except that no gun at that time was capable of firing at such a rate. The first aircraft tests were in August 1916 but it did not go into service until March 1917. There were significant teething problems, but the British persevered and the CC gear became their standard system until synchronised installations were abandoned during WW2. American and Japanese air services also adopted this system towards the end of WWI, although the USA subsequently developed the Nelson gear which formed the basis for later designs.

The French copied the Fokker gear, appropriately modified for the Vickers gun (the only Allied gun suitable for synchronisation) which entered service in the summer of 1916. A later mechanism was designed by Marc Birkigt (who went on to design the Hispano-Suiza HS 404 cannon). The Italian Revelli could be synchronised although it was not well suited to it. The Russians briefly used a Lavrov-designed gear to operate a Colt M1895 or Vickers attached to the Sikorsky S-16ser, but this only saw service in the Spring of 1916 before being rejected as unreliable. Most other nations used British, French or German systems. The Austro-Hungarians had to develop synchronisation gear suited to work with the Schwarzlose retarded blowback gun. The Zaparka gear fired the gun on every fourth propeller revolution, and the quoted rate of fire (RoF) dropped from 590 to 380 rounds per minute (rpm) for the M16 or from 880 to 500 rpm for the M16A. The mechanism could be relied on only within a band of engine revolutions between 1000 and 1600 rpm with the M07/12, and 600 to 1600 rpm with the MG 16. This explains the very prominent place given in the cockpit of fighters to a large engine tachometer. The Bernatzik and Daimler gear reduced the RoF even more, by 55% in the case of the M16. However, the Daimler gear did have the advantage that the M16 could be safely fired from engine idle to 1600 revolutions per minute, although the M07/12 was still restricted to a 1100 – 1600 rpm band. At the end of the war the Austro-Hungarian forces decided the standardise on the Priesel system.

As well as mechanical and hydraulic linkages, electrical synchronisation gear was developed in Germany and Austro-Hungary and tried before the end of WWI. This used contacts on the propeller hub or shaft to send signals to a solenoid on the gun, which fired the trigger. LVG built forty C.IV planes fitted with a Siemens electrical gear and the Aviatik company received instructions to fit fifty of their own systems to DFW C.Vs. Such systems were to become much more important in the next great conflict over twenty years later.

Synchronisation issues

Synchronisation was the best solution available at the time to the problem of arming front-engined fighters, but it was not ideal. The gears were complex and even the CC type required careful maintenance to keep them properly adjusted. When they failed, they sometimes resulted in the pilot shooting off his own propeller. Many Austro-

Hungarian fighters were equipped with the Kravics propeller hit indicator, which consisted of electric wiring wrapped around the critical area of the propeller blades, connected to a light in the cockpit by a slip ring on the propeller shaft. If the light went out, the pilot knew the propeller had been hit!

A major contributor to synchronisation problems (and gun reliability generally) was ammunition quality, which tended to be variable during the War. Pilots frequently carried a mallet with which to hammer the loading lever in order to chamber a recalcitrant cartridge. In an attempt to resolve this, the British introduced in 1917 "Green Label" (or "Green Cross") .303 inch ball ammunition specifically for synchronised guns. This was taken from standard production lines, but carefully selected from batches which complied with tighter manufacturing tolerances and gave reliable ignition. This proved successful and was followed up in 1918 by establishing special production lines to make high quality ammunition for this purpose. This was known as "Red Label" (also as "Special for RAF, Red Label", "Special for RAF" and finally "Special") and ball, AP and SPG tracer ammunition were produced.

Synchronisation systems reduced the gun's natural rate of fire; by how much depending on a variety of factors. The first factor was a gun whose firing mechanism could be controlled separately from the action of the bolt. As we have seen, the Lewis gun did not have this feature and the initial efforts at synchronisation resulted in a RoF of only 100-150 rpm, less than a quarter of the normal rate. The later Alkan gear managed to increase this to 160-200 rpm, and a more thorough redesign of the firing mechanism by Hazleton did see some limited use, but by then the Vickers had been accepted as standard. The second factor was a precise and reliable synchronising gear. The more accurate it was, the lower were the safety margins required and the greater the number of degrees of the propeller disc available for firing. The third factor was the gun's normal RoF; the higher this was, the greater the percentage loss through synchronisation (other things being equal). The final factor was the number of propeller blades; the more there were, the more critical accurate timing became.

The RoF of a synchronised gun tended to be rather erratic because it varied with propeller speed. Theoretically, it was possible to achieve an ideal match between the propeller rpm and gun's natural RoF, so that the gun was not slowed down at all. However, such harmony would obviously disappear as soon as the engine slowed down or speeded up. This particular problem was not solved until the adoption of the constant-speed propeller, which was uncommon until the late 1930s.

The effect of synchronisation on the RoF can best be explained by describing a simple system like that introduced by Fokker, in which one firing signal was sent to the gun for each rotation of the propeller. If the gun was capable of firing at 500 rpm, then for propeller speeds of up to 500 rpm the RoF would be the same as the propeller rpm. However, as soon as the propeller exceeded 500 rpm, the gun mechanism could no longer keep up and could then only fire on every other rotation, so the RoF would drop to 250 rpm. It would then accelerate again with increasing propeller speed but at half the rate, so when the propeller was spinning at 1,000 rpm, the gun would be back to firing at 500 rpm again. Once more, propeller revs faster than this would cause the RoF to drop, but this time only to two-thirds of the full RoF, as it would fire on every third rotation, so it would be achieving 330 rpm. As the propeller continued to accelerate to 1,500 rpm, the gun would be back up to 500 rpm again, and so on.

Any quoted figure for synchronised rates of fire could therefore only be an average. It is also worth repeating that quoted RoFs for unsynchronised guns were only averages also, with the actual RoF for different examples of the same type of gun varying quite significantly depending on age and maintenance. Any one gun might also vary in its rate of fire depending on the ammunition used, on the effect of the low temperatures experienced at high-altitude in congealing the gun lubricants and on the variable G-forces consequent on manoeuvring.

More advanced systems like the CC and the later German types sent two firing signals per propeller revolution (logical with a two-bladed propeller, in which there would be two firing opportunities per revolution), although possibly at the expense of some reliability in these primitive early systems, as they would have to work twice as fast. In this case, the maximum RoF for our 500 rpm gun would be reached twice as often, at 250, 500, 750, 1,000, 1,250 and 1,500 rpm. A still more sophisticated variation was to use a “critical sector cam”, which instead of just sending a single firing impulse sent a continuous one during the “safe” period when the propeller blades were out of the way. The effect of this was much less regular, with the gun firing in erratic bursts, but the average RoF was the highest of all.

In the vast majority of cases at this time, the engine directly drove the propeller so the propeller revs were the same as the engine revs. Rotary engines ran at around 1,200-1,300 rpm, the six-cylinder in-lines favoured by the Germans at 1,200 rpm at the start of the war and 1,400-1,500 rpm by the end, the Hispano-Suiza used in the SPAD at 1,600 rpm, and the Rolls-Royce Falcon V-12 used in the Bristol Fighter at 1,800-2,250 rpm, depending on the version. In the case of geared engines (which saw relatively little use in the First World War, the main fighter example being in some installations of the Hispano-Suiza V-8) then it was clearly the propeller rather than engine speed which determined the synchronisation conditions.

Taking all of this information together it becomes possible to understand the different national choices in regulating the gun RoF. With their in-line six-cylinder engines running at 1,400-1,500 rpm, the Germans' Maxim would have had to have been capable of about 800 rpm to take full advantage of a firing impulse every other rotation. It could not do this, so it made sense to adjust it to fire approximately every third rotation and thereby enjoy the benefits of greater reliability of both gun and synchroniser gear and reduced gun heating problems; the Maxim was in fact normally set at around 450 rpm. The introduction in 1917 of the Hazleton gear to the British Vickers enhanced the RoF to 850-900 rpm, which in combination with the fast-acting and more reliable CC gear would fire twice for every three rotations of a rotary engine, or every other rotation with the faster-running V-8 and V-12 engines.

A practical example of the effect of synchronisation is graphically provided by comparative tests held by the USN in 1926/7 of the .30 inch (7.62 mm) M1921 and .50 inch (12.7 mm) M1921, both on a test stand and in synchronised mountings. These also shed some light on the differences between claimed and actual rates of fire, and between different installations of the same gun. The .30 had a claimed RoF of 1,200 rpm, but proved capable of between 800 and 900 rpm on the test stand. When synchronised, the RoF went down to an average of 730 rpm (a fall of about 15%), with a range of between 667 and 818 rpm for different installations and propeller speeds. The .50 had a claimed RoF of 600 rpm, and did rather well to achieve between 500 and 700 rpm, depending on the recoil buffer adjustment (although a contemporary British report put this at 400-650 rpm, the difference possibly caused by belt drag when installed), but this fell to an average of 438 rpm when synchronised, varying between 383 and 487 rpm. As the synchronised guns were adjusted for maximum RoF, this represented a reduction of around 37%. There is no inherent reason why a larger calibre weapon would suffer a bigger reduction in RoF, so the synchronisation conditions must have been better suited to the .30 in gun's natural RoF.

One approach to central gun mounting was to arrange for one gun to fire through a hollow propeller hub; it therefore needed no synchronisation and could fire at full rate. The problem was that, with a front engine, this was only possible with a vee-engine and a geared propeller; the gun was mounted on the engine block, between the cylinder banks, and the propeller axis was offset so that the gun barrel was in line with the hole through the propeller hub. This was tried in a few aircraft in WWI but was much more popular in WW2, especially in German and Soviet fighters. However, just one gun was not enough, so their aircraft designers still faced the problem of how to mount the other guns.

World War 2

The RAF and USAAF resolved synchronisation problems during WW2 by adopting wing-mounting for all fighter guns, but not every nation preferred this. There were still many followers of cowling-mounted and synchronised guns because the concentration of weight in the centre of the aircraft was beneficial for handling (specifically roll acceleration), engine heat prevented gun freezing and harmonisation wasn't a significant problem, as fire would be concentrated horizontally at all ranges (although the trajectory curve of the projectiles meant that sights still had to be adjusted for some particular range). However, nose-mounted guns concentrated weight well forward of the centre of gravity (not good for other aspects of handling) and there could be a noticeable change in CG between full and empty ammunition tanks. Also, the number of guns which could be fitted around the engine was limited, and even the best synchronisation system (and there were some poor ones even then) reduced the rate of fire.

This can be demonstrated by some British calculations performed postwar on the effects of synchronisation on different types of weapon. It must be borne in mind that propeller blades swept past the gun muzzle at a much faster rate than any gun could fire. With a three-bladed propeller rotating at a typical 1,200 rpm, a blade went past the muzzle 3,600 times per minute. Gun synchronisation was therefore about choosing the correct instant for firing each shot, not about occasionally interrupting the automatic fire. The calculations showed that a gun firing at 1,200 rpm would have its firing rate slowed by an average of 12.5%; and as much as 25%, depending on the synchronisation arrangements. At 800 rpm the average reduction was 10% and at 600 rpm about 7%.

It is however difficult to find many actual examples of the effects of synchronisation on rate of fire. The Soviet 12.7 mm UBS was stated to fire at 800 rpm instead of 1,050; a reduction of 24%. It also appears that the ShKAS was slowed from 1,800 to 1,300 – 1,500 rpm (17 – 28%) depending on the installation, and the ShVAK from 800 to 700 (12.5%).

Some installations appeared to be even worse than this; tests of cowling-mounted .50 M2 in US aircraft revealed RoFs of 400–450 rpm, and anecdotal reports of the Japanese 12.7 mm Ho-103 (which shared the M2's Browning short-recoil mechanism) indicate a similar problem. Aircraft without constant-speed propellers also suffered considerable variations in RoF depending on the engine speed. This was a particular complaint the Finnish pilots had with the 12.7 mm Breda-SAFATs in their Fiat G.50s, which at certain engine revs could be slowed right down.

An important aspect of synchronisation was the safety margin left around each propeller blade to make certain that any inaccuracy in synchronisation would not cause the blade to be struck (obviously particularly important with HMGs or cannon). The more precise and reliable the control of the instant of gun firing, the smaller the safety margin could be and the less the gun's rate of fire would be affected. For this reason, Germany developed the use of electric ignition for their larger aircraft guns. The instant of firing was electrically transmitted directly from contacts on the propeller or engine to the cartridge for the closest possible control. Instead of a chemical primer being struck by a firing pin after it had travelled forward for a short distance, electric primers were triggered almost instantaneously by having an electric current passed through them. In appearance, the electric primers looked the same as percussion ones, except for an inner ring of insulation, but the two types were not interchangeable; percussion and electric-primed guns would only function with their associated ammunition. The result of this attention to synchronisation was that the loss in RoF appears to have been kept to about 10%.

The 7.92 mm German MG 17 retained percussion priming and was able to utilise open-bolt firing (with the benefit of reducing the risk of ammunition cook-off in a hot chamber) by having two sears. The sear holding the bolt open was released by the pilot pressing the firing button, but once the bolt was closed there was a second sear holding back the firing pin, and that was released by the synchronisation system, via an electrical solenoid. The RAF's .303 inch Browning utilised a similar system in the small number of aircraft using synchronised installations early in WW2 (most notably the Gloster Gladiator). Incidentally, the USAAF Brownings fired from a closed bolt; their gun propellant was less inclined to cook-off than the British Cordite.

The most efficient solution to synchronisation was represented by the Hungarian Gebauer GKM and Czech Brno ZB-80, in which the gun's speed and firing rate were driven directly by the engine. Very high firing rates were therefore possible. However, these weapons were much less flexible in their application, as they could only be fitted within engine cowlings. In theory they could have been driven by electric motors to permit their installation in other locations, but there is no indication that this was tried.

One additional point about synchronisation is that the size of the cartridge in larger calibres became an issue. The German MK 103 30 mm cannon had electric priming so in theory could be synchronised, and there was a proposal for wing-root mountings in a Ta-152 variant, but in practice it did not work. The problem was that the very large quantity of propellant in the big cartridge had an unpredictable burning time, so the time gap between the primer being fired and the shell leaving the muzzle varied too much for effective synchronisation – and pilots did not want to risk hitting their own propeller blades with a 30 mm shell!
