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The History of Positive Feedback:

The Oscillating Audion, the Regenerative Receiver, and other applications up to around 1923

Professor D. G. TUCKER,
D.Sc., C.Eng., F.I.E.E., F.I.E.R.E.*

SUMMARY
Positive feedback, or regeneration, played an important part in radio engineering during the two or three decades following its development for electronic circuits around 1912–15. This paper reviews the earlier history of the subject, considers the controversial inventions of 1912–15 in some detail, and goes on to examine some other applications of positive feedback in self-oscillating detectors, e.g. the autodyne, the homodyne and the super-regenerative receivers.

* *Department of Electronic and Electrical Engineering, University of Birmingham, Birmingham B15 2TT.*

Contents

1. Introduction

1.1. *General Observations*

Positive feedback, as something deliberately intended, is nowadays of much less significance than negative feedback, which forms the basis of control systems. In terms of mechanical systems, negative feedback in the form of governors was important long before positive feedback was recognized either implicitly or explicitly. But in electronic circuits it was the other way round; positive feedback for a couple of decades from 1912 reigned supreme, and negative feedback was something 'invented' for electronic systems around 1930.

In positive feedback part of the output signal is fed back to the input in such a way as to reinforce the signal in the input. This has the effect of increasing the gain of an amplifier, and, by reducing the damping of any tuned part of the amplifier, increases the sharpness of tuning (i.e. reduces the bandwidth). If the feedback is sufficient, the oscillations in the system will become self-sustaining, the input signal can be removed, and an oscillation-generator is obtained. The liability to break into self-oscillation if parameters of the system change is one of the difficulties of using positive feedback for amplification. In the early days of radio, the ability to obtain a high sensitivity was so important that the difficulties of positive feedback (usually then called reaction or regeneration) were not regarded as serious.

As in many other aspects of electronic and radio engineering, ideas of feedback developed without much regard to theory and knowledge already existing in other fields of science and engineering. Therefore, although we must start our account of the history of positive feedback with a consideration of instability and oscillation in mechanical governors, it is nevertheless true to say that this topic had no influence on the development of electronic systems.

1.2. *Outline of the Scope of this History*

Early governor and control systems used *negative* feedback in a usually simple mechanical form in which instability was unlikely. It is therefore improbable that *positive* feedback was ever recognized before the second half of the 19th century, when Clerk Maxwell drew attention to it (although not by that name), and analysed it in terms of instability in governors.

In the early years of the 20th century telephone repeaters (i.e. amplifiers) were made essentially of telephone receivers coupled to microphones, and it was known that when the output was coupled to the input the repeater could 'howl', i.e. generate self-oscillations.

The development of the audion, the first thermionic triode, by de Forest from 1906 onwards, led to the development of electronic amplifiers, and eventually positive feedback was 'invented' in relation to such amplifiers from 1911 onwards. Two applications emerged; one, the generation of oscillations, and the second, the increase in amplification produced by feedback below the critical amount required to produce oscillation. Both these applications had enormous commercial value in the rapidly-growing field of radio communication, and there were in consequence repeated and fierce legal battles over priority of invention, mainly between de Forest and Armstrong.

From the idea of positive feedback, otherwise known as reaction or regeneration, Bolitho and Armstrong went on to develop the super-regenerative receiver, while others used the positive feedback in different kinds of self-oscillating detectors represented by the two main systems: the autodyne and the homodyne.

Well within a decade of the invention of feedback electronic oscillators, the non-linear nature of the oscillation process in real circuits was recognized and examined mathematically, notably by van der Pol.

With the growth of better amplifying devices, the use of positive feedback to increase amplification, with its attendant risk of instability, gradually disappeared. However, the use of positive feedback to produce controlled self-oscillation is still important.

It is hoped that the present review of the history of positive feedback, viewed from a distance of over half a century, will put the matter in reasonable perspective.

2. Mathematical Concepts of Instability in Governors

It may come as a surprise to some that the famous James Clerk Maxwell, so well known for his work in electromagnetism, should have published[1] a classic paper 'On governors' in 1868. In introducing his analysis, Maxwell says:

'It will be seen that the motion of a machine with its governor consists in general of a uniform motion, combined with a disturbance which may be expressed as the sum of several component motions. These components may be of four different kinds:

1. The disturbance may continually increase.
2. It may continually diminish.
3. It may be an oscillation of continually increasing amplitude.
4. It may be an oscillation of continually decreasing amplitude.

'The first and third cases are evidently inconsistent with the stability of the motion; and the second and fourth alone are admissible in a good governor. This condition is mathematically equivalent to the condition that all the possible roots, and all the possible parts of the impossible roots, of a certain equation shall be negative.

'I have not been able completely to determine these conditions for equations of a higher degree than the third; but I hope that the subject will obtain the attention of mathematicians.

'The actual motions corresponding to these impossible roots are not generally taken notice of by the inventors of such machines, who naturally confine their attention to the way in which it is *designed* to act; and this is generally expressed by the real root of the equation. If, by altering the adjustments of the machine, its governing power is continually increased, there is generally a limit at which the disturbance, instead of subsiding more rapidly, becomes an oscillating and jerking motion, increasing in violence till it reaches the limit of action of the governor. This takes place when the possible part of one of the impossible roots becomes positive'.

Maxwell does not specifically relate this condition to positive feedback as such, but it can be seen from his mathematical analysis that in a typical system instability takes place when the time constants and the control sensitivity (i.e. loop gain) are high enough—in other words when the feedback is positive and large enough. So the role of positive feedback in generating oscillations is at least implicitly established by 1868, even though it is not yet explicit.

In passing, it is interesting to note Maxwell's modesty in not regarding himself as a mathematician, and his gentle reproof of inventors for insufficient attention to the real modes of operation of their machines.

3. Positive Feedback and Oscillations in Electromechanical Systems

It has been stated by many writers that the ability of an amplifying system to oscillate when the output is coupled back to the input was discovered by the users of the early telephone repeaters, which were electromechanical in nature. Although there were several proposals for telephone repeaters just after 1900,[2] the commonest was that based essentially on a telephone receiver coupled mechanically to a microphone. It was to be expected that at some time the output of one of these devices would get coupled to the input and an oscillation would result (at a frequency where the phase relations were right). Judge Mayer referred specifically to this effect in his judgement in the Armstrong–de Forest litigation and also referred to a book by Miller[3] where it is mentioned.

With this prior knowledge of oscillation, it is perhaps a matter for surprise that feedback was not applied deliberately to make an oscillation generator earlier than it was. Its use in increasing the gain of an amplifier was rather more subtle and was more understandably delayed.

4. Positive Feedback in Electronic Circuits, 1911–1915

4.1. *The General Situation*

The story of the invention (or discovery), understanding and development of the idea of positive feedback in electronic circuits is a very complicated and confused one. Because of the commercial importance of the idea, there was a great deal of patent litigation over it, and a great deal of public attention was drawn to it. It is one of the famous (or notorious!) cases of engineering history, and consequently much has been written about it. Practically every book which discusses the history of radio[4] gives some account of it; yet there is little consistency among the various accounts (except where one is copied directly from another, as happens occasionally), and all seem to be inaccurate or incomplete to a greater or lesser extent.

The question of who really was the inventor of positive feedback is not now of much importance. The word 'invention' is itself not entirely appropriate for positive feedback; 'discovery' would be better. The legal wrangles were concerned with awarding patent priority in the United States, and therefore considered only inventors who had filed patents in the United States. Scant (if any) attention was given to inventors who had either filed no patent, or had failed to extend their patent cover to the United States. Nevertheless, the judgement of District Judge J. M. Mayer[5] in 1921 is one of the most interesting accounts of the invention available. This judgement awarded priority to Edwin H. Armstrong, but was subjected to several appeals[6] and counter-appeals, finishing in the Supreme Court of the U.S.A., which in 1934 awarded priority to Lee de Forest.

Whatever the legal judgements were at any time, the radio engineering profession seemed to consider Armstrong the true inventor, or at any rate the man who made the biggest contribution to the development of the reaction circuit and the generation of oscillations. In 1917 (or at any rate, for the year 1917) the Institute of Radio Engineers (U.S.A.) awarded its first Medal of Honor to Armstrong 'in recognition of his work and publications dealing with the action of the oscillating and non-oscillating audion.'[7] In 1934, following the Supreme Court's award of priority to de Forest, Armstrong wished to return the medal to the Institute. The Board of the Institute, however, insisted on his keeping it, with the words[8]

> 'That the present Board of Directors, with full consideration of the great value and outstanding quality of the original scientific work of yourself and of the present high esteem and repute in which you are held by the membership of the Institute and themselves, hereby strongly reaffirms the original award, and similarly reaffirms the sense of what it believes to have been the original citation.'

Armstrong, as is well-known, went on to make many other important inventions and developments, e.g. super-regeneration and frequency-modulation, and his reputation greatly increased; he was awarded the Edison Medal of the American Institute of Electrical Engineers in 1942.[9]

The men named by various authors as having been concerned in the invention of positive feedback are (in alphabetical order):

Edwin H. Armstrong (U.S.A)	Eugen Reisz (Austria)
Lee de Forest (U.S.A.)	Henry J. Round (U.K.)
Charles S. Franklin (U.K.)	Wilhelm Schloemilch
Irving Langmuir (U.S.A.)	Siegmund Strauss (Austria)
Charles V. Logwood (U.S.A.)	H. B. Van Etten (U.S.A.)
Fritz Lowenstein (U.S.A.)	Georg von Arco (Germany)
Alexander Meissner (Germany)	Otto von Bronk

Of these, we can dismiss from further consideration, on the grounds that their patents, cited in the literature, show no use of, or knowledge of, positive feedback, the following:

Langmuir[10]	Schloemilch and von Bronk.[11]

We have also to dismiss Strauss, as the only citation[12] gives no detailed reference, and the author has so far found no other information on him or his work.

Logwood and Van Etten were assistants to de Forest, and inventions and discoveries attributed to de Forest may well be actually due to his assistants.

Meissner and von Arco appear jointly in patents, but it is believed that Meissner was the inventor, and thus we shall refer no more to von Arco.

4.2. *The Technical Background*

By 1912 the audion, as the triode thermionic valve was then known, was six years old, having been invented in 1906 by de Forest.[13] In passing we may note that a bitter legal battle was fought over priority of invention here too, for Fleming held that his invention[14] of the thermionic diode in 1904 gave him priority in all developments of the thermionic valve.

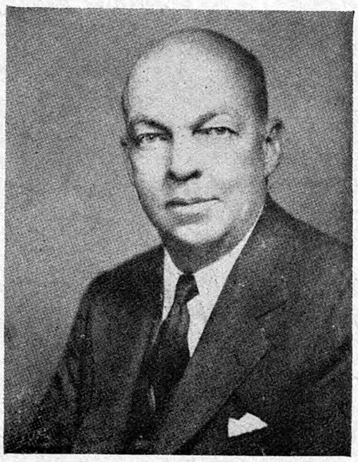
The audion was not well understood—it seems clear from his own writing that de Forest did not understand it—but it did develop slowly. It was Armstrong who first put the design of circuits using it on a sound quantitative basis by introducing the idea of characteristic curves and oscillographic examination of waveforms.[15,16] The gain of a single audion stage was low, so the invention of cascade or multi-stage circuits was important.[17] The use of negative grid-bias was patented by Lowenstein in 1912,[18] and the grid-leak and capacitor by Round in 1914[19], although demonstrated by him in 1913.[20]

With this amount of development going on, with the need for ever-greater amplification and the need for better sources of high-frequency oscillations than the spark, the Poulsen arc and the rotating alternator, it is really not surprising that amplifiers were found to oscillate and that feedback should be discovered around 1912–13.

Against this background we shall now examine the contribution of the main inventors, Armstrong, de Forest, Franklin, Lowenstein, Meissner, Reisz and Round.

4.3. *Armstrong*

Armstrong's patent application[21] for his feedback amplifier was filed on 29th October 1913. The specification is rather a complicated one, but basically it relates to an amplifier–detector in which the detection sensitivity is increased by positive feedback of the *audio* signals in the wing (i.e. anode) circuit to the grid circuit.



Professor Edwin H. Armstrong
1890–1954.

Coupling between anode and grid circuits is generally by means of a common reactance in the cathode circuit which is arranged to be effectively a short-circuit at the radio frequencies. Thus only the rectified and smoothed (i.e. audio) signals are fed back. However, Armstrong does also envisage r.f. feedback. Two claims (Nos. 9 and 15) make these two types of feedback quite clear:

'9. An audion wireless receiving system having a wing circuit interlinked with a resonant grid circuit upon which the received oscillations are impressed, and an inductance through which the current in the wing circuit flows, the grid circuit including connections for making effective upon that circuit the potential variations resulting from a change of current in the wing circuit.'

'15. An audion wireless receiving system having a wing circuit interlinked with a resonant grid circuit upon which the received oscillations are impressed, and means supplementing the coupling of the audion to facilitate transfer of energy from the wing circuit to the grid circuit, whereby the effect upon the grid of high frequency pulsations in the wing circuit is increased.'

The matter is made much clearer in his paper of 1915, where indeed he shows a circuit[22], redrawn here as Fig. 1, which provides specifically for feedback at both radio and audio frequencies, using a separate transformer for each.

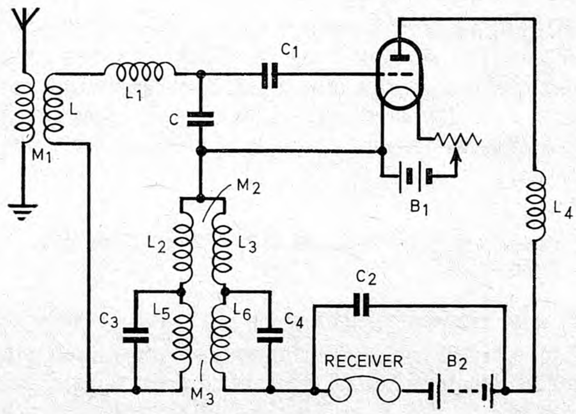


Fig. 1. Armstrong's circuit for combined r.f. and audio feedback.

'Here M_2 represents the coupling for the radio frequencies and the coils are of relatively small inductance. M_3 is the coupling for the audio frequencies, and the transformer is made up of coils having an inductance of the order of a henry or more. The condensers C_3 and C_4 have the double purpose of tuning M_3 to the audio frequency, and of by-passing the radio frequencies. The total amplification of weak signals by this combination is about 100 times, with the ordinary bulb. On stronger signals, the amplification becomes smaller as the limit of the audion's response is reached.'

There is no room for doubt that Armstrong understood positive feedback and saw its main importance in terms of amplification. He was perfectly aware, however, that it could generate high-frequency oscillations, for in his patent specification he says:

'I find that the audion is made more stable and shows less tendency to become a high frequency generator and to set up oscillations in the interlinked circuits, if the tuned grid circuit is grounded....'

In the Armstrong *v.* de Forest litigation, the courts were at pains to establish which of them first discovered feedback in this context, not who first patented it. This meant that the whole story of how Armstrong came to work on the topic had to be stated, and Judge Mayer gives an excellent account of this in his judgement of 1921.[23] In brief, Armstrong started radio experimenting at the age of 15, and was working on the audion amplifier in a scientific manner while still an undergraduate at Columbia University, where he graduated at 22 in 1913. By the autumn of 1912 he had made an audion receiver of extreme sensitivity, and demonstrated it during the winter without disclosing his circuit. He had insufficient money to file a patent, but on 31st January 1913 he had a drawing of the circuit witnessed by a notary. Judge

Mayer therefore established the date of invention as 'at least as early as January 31st, 1913'.

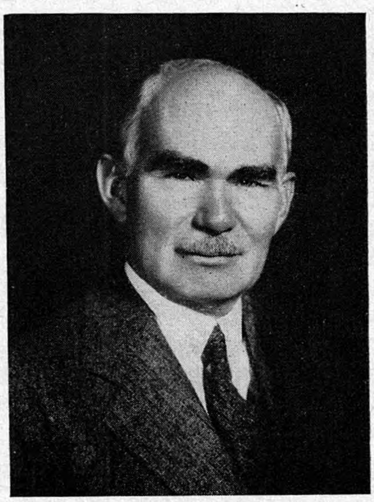
Armstrong's patent was quickly taken up commercially, licences being granted to the Atlantic Communication Co., the Goldschmidt Co. and the Marconi Co.

One point of interest is that Armstrong did not mention (in his patent or in his 1915 paper) the sharper tuning provided by feedback; the emphasis was entirely on increasing the amplification. The concept of positive feedback reducing the damping of the circuit apparently escaped him.

4.4. *de Forest*

In contrast to Armstrong's very professional and scientific approach to radio, de Forest appears almost as a fumbling amateur. In his patent specifications as in his published papers, he shows little understanding of what he is doing. Judge Mayer was not impressed by him:

> 'On the one side is...Armstrong...and he produces a sketch which is extraordinary for its clear and unmistakable description...
>
> 'On the other side is a then experienced and able worker... who is unable to rely solely on notebook entries which are not clear but require construing and who supplements these entries by recollection which is fallible and not certain.'



Photograph Science Museum, London

Dr. Lee de Forest
1873–1961.

As far as patents and publications are concerned, de Forest showed no explicit use of positive feedback until 26th March 1915 when he filed a patent[24] showing in one figure a feedback coil in a mercury-valve circuit (merely as an option to enhance the oscillation) and 13th May 1915, when Fig. 2 of his patent filed that day[25] showed a rather casual use of a feedback transformer:

> 'If desired the grid and plate circuit may be inductively associated with the plate and filament circuit through inductance L, as shown.'

In fact L was a transformer. 'Plate' is, of course, the anode. The circuit was that of an 'oscillation generator' in an aerial circuit and is redrawn in Fig. 2 of the present paper. De Forest used rather peculiar electrode connexions, as can be seen. The oscillation current in the aerial could be keyed or modulated by a microphone as shown. Actually de Forest used an audion with two grids connected in parallel and two anodes also in parallel, but this could not have been fundamental to the operation.

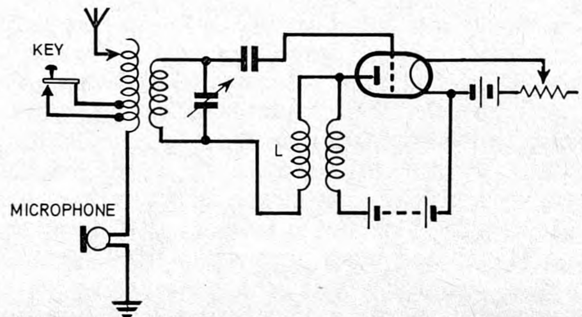


Fig. 2. De Forest's circuit of 1915 for oscillating audion.

It is clear that at this stage, de Forest still did not use feedback explicitly. In most of his circuits he obtained oscillation because of the anode-grid capacitance associated with inductive loads elsewhere—but he never recognized this; not at any rate until many years later. In his published paper of 1914[26] he similarly does not mention feedback. Note that he had earlier patents on the oscillating audion[27,28], but these had no explicit feedback.

Judge Mayer regarded de Forest's patent of September 1915[29] as the first showing feedback claimed as such.

In the light of all this the evidence produced in the patent suits that de Forest had invented feedback in 1912 seems extraordinary. In the Mayer judgement, reference is made to work done by de Forest's assistant Van Etten, who kept a notebook.

> 'Van Etten was working on the audion as a telephone relay and amplifier. On July 23rd (1912), he entered in this notebook a two-way telephone circuit using two audions...they did not have two audions available and on July 24th Van Etten attempted to set up this two-way circuit of his with a single audion having two grids and two plates. The arrangement did not work....
>
> 'The following day, August 6th, he connected the input circuit of a double audion to the output circuit and in this accidental way found that the audion would howl or sing....
>
> 'From this point on his notes show a continuing attempt to produce a telephone relay circuit in which the audion would not howl and in this effort he succeeded on or about August 29th, 1912.
>
> 'The August 6th, 1912, entry of Van Etten was not copied in the laboratory notebook nor was anything done which showed that any one appreciated the phenomenon. De Forest's testimony on the point is not sufficiently clear and definite to be satisfactory.'

A photograph of the Van Etten notebook entry is reproduced in an article[30] on a later suit, which also reproduces a sketch made by Dr. John Stone (American Telephone and Telegraph Co.) of a feedback oscillator circuit shown him by de Forest two years earlier in 1913.

The fact that successive courts so often alternated in their decisions on the case (an oscillation not due to feedback?) is sufficient indication of how contradictory was the evidence.

We should note before leaving de Forest that in 1950 he published a long autobiography[31] in which, as would be expected, there is substantial discussion of the feedback invention, one chapter being devoted to it and another to the litigation over it. It is very fascinating reading. We can, of course, hardly regard this autobiography as objective history and consequently shall not quote from it. Sufficient is it to say that he portrays Judge Mayer (and other judges who ruled against de Forest) as completely prejudiced in Armstrong's favour and unconcerned with justice, he speaks of Armstrong as an enemy, and explains how the case had to go before the Supreme Court twice. Perhaps one can understand how, in a case involving so many millions of dollars, feeling ran so high and one may suppose that Armstrong also had strong feelings.

4.5. *Franklin*

After the confusion of de Forest's work it is refreshing to turn to that of Charles S. Franklin of the British Marconi's Wireless Telegraph Company. His patent specification[32] of 12th June 1913 describes a regenerative amplifier thus:

'. . . we make the circuit, in which the magnified oscillations occur, react on the circuit, in which the oscillations to be magnified occur, by coupling these circuits, either electrostatically or electromagnetically, to a certain degree.

'If the coupling be too strong the tube will be unstable and will itself tend to produce oscillations but there is a certain critical strength of coupling below which the tube is unable to maintain oscillations. At a coupling a little below this critical strength the tube and circuits are stable but act while receiving oscillations as though the resistance in the circuits was very small.

'The result is that the damping of the receiving system can be reduced to any required degree and the tuning of the system is made very sharp'.

Franklin's circuit is redrawn in Fig. 3 and can be seen to show the feedback quite explicitly by a special loop connexion.

It is not quite certain that Franklin invented positive feedback (as such) independently, for he had apparently visited Meissner in Germany not very long before[33] and had learned that Meissner had succeeded in making a thermionic valve oscillate continuously. However, as we shall see, Meissner appeared to be concerned only with the generation of oscillations, and it is more than likely that Franklin thought out for himself the other useful application of feedback to make sensitive radio receivers.

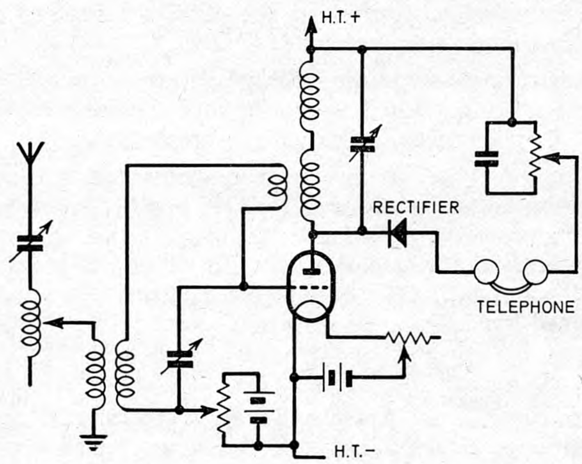


Fig. 3. C. S. Franklin's regenerative receiver of 1913.

It is interesting that Franklin is the only one of the inventors we are considering who mentions the effect of feedback in reducing the damping and sharpening the tuning. Yet this was an important property of the system and could be both a benefit and a nuisance in practice—a benefit in making the receiver more selective, and a nuisance in making it difficult to maintain a receiver in tune for a long period.

The idea of resistance causing damping in a resonant circuit was, of course, quite old even in 1913. As far back as 1853, Kelvin[34] had developed the equations for what was effectively an R, L, C circuit in studying the discharge of a capacitor through a conductor. He established that the energy of the charged capacitor at any instant during discharge was partly dissipated as heat (in the resistance) and partly conserved as current energy in the circuit. Blanchard[35] gives a full discussion of the history of electrical resonance, so we need only say here that the first application of resonance to obtain selectivity in radio receivers was by Sir Oliver Lodge[36] in 1897. The idea that an amplifier could be used to reduce the resistance or damping of a tuned system and so sharpen the tuning does seem to be due to Franklin, and it is an important concept.

The author has so far been unable to establish when Franklin started work on positive feedback. His patent gives every appearance of having been based on experimental trials, and it is possible he was as early as Armstrong; his patent was much earlier than Armstrong's. He did not, however, take out a United States patent (as far as the author can trace) and this accounts for his omission from the U.S. litigation.

4.6. *Lowenstein*

The evidence concerning Lowenstein's contribution to the invention or development of positive feedback is both intriguing and unsatisfactory—intriguing because his work appears to be the very earliest of all work on the oscillating audion, and unsatisfactory because there is no record by Lowenstein himself nor any proper documentary evidence of what he did. All that we have are recollections by his contemporaries, recorded long afterwards. But these do add up to a fairly strong case for believing that Lowenstein had a reliable audion oscillator towards the end of 1911 or early 1912.

The recollections concerned are contained in a long article by Hammond and Purington,[37] a long discussion on this by Espenschied,[38] and in a book by Miessner.[39] All three of these are mainly subjective or personal views of the early history of radio by people who were themselves very much involved in making that history and they are very far from being impartial; indeed they are extremely controversial. There is agreement among them, however, that Lowenstein had an audion oscillating by the end of 1911, and that his circuit and arrangements are not recorded or patented.

Espenschied says:

> 'One wonders too that the evidence of Lowenstein's having the audion as an oscillation generator during the winter of 1911–1912 was not presented to the courts in the long de Forest–Armstrong litigation over the oscillating tube. Such evidence would have demonstrated the natural tendency of an amplifier to oscillate and hence how little inventior there was in the oscillating audion *per se* once it had become an amplifier.'

One may question the philosophy of this remark. Was there really only very little invention in realizing that positive feedback was necessary for oscillation, and working out how best to arrange it? Certainly one can appreciate that invention *was* involved in the feedback or regenerative amplifier, as distinct from the oscillator, and there is nothing fortuitous or fumbling in the patents of Armstrong and Franklin.

4.7. *Meissner*

Alexander Meissner worked in Berlin with a slightly different type of valve, the Leiben–Reisz valve, but like the audion, it was a triode and his circuits are therefore comparable. There seems no doubt that he had a working oscillator by at latest the beginning of 1913, and his German patent[40] is based on several applications from 10th April 1913 onwards. His circuit shows that his positive feedback was quite deliberate; it is redrawn in Fig. 4. There seems no provision here for using it as an amplifier. However, in British and United States patents[41,42] filed early in 1914, Meissner (and his co-patentee von Arco) gives a masterly treatment of the applications of positive feedback in oscillators, amplifiers, amplifier-detectors and heterodyne receivers. For scope and adequacy of understanding, these descriptions are the best of the whole lot dealing with positive feedback; only sharpness of tuning seems to be omitted.

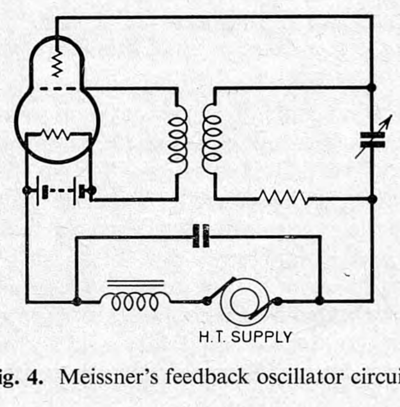


Fig. 4. Meissner's feedback oscillator circuit.

Without further evidence one cannot tell how priority should be allocated between Meissner and Franklin; since they are known to have discussed the subject together, it is possible their inventions were not strictly independent of each other.

4.8. *Reisz*

Eugen Reisz, of Austrian nationality but working in Germany, filed a patent in the U.S.A. on 9th April 1913 in which he showed an amplifier provided with a feedback connexion by means of an anode–grid transformer coupling. There is no doubt that he intended this to be a regenerative amplifier, for he says that when the phases are right

> 'then the amplitudes of the currents reinforced by the relay [i.e. valve] always become greater.'

Judge Mayer said that this patent did not call for discussion in relation to the Armstrong *v.* de Forest priority dispute. Perhaps on some legal grounds he may have been right, but on technical grounds Reisz's patent seems very relevant. Admittedly it was presented in terms of an amplifier for telephone lines and not for a radio receiver, but this was a trivial distinction and the patent covered other applications in general terms.

4.9. *Round*

Although H. J. Round is mentioned in some of the texts as an inventor of positive feedback, it seems from his patent specifications that he was rather an inventor of new systems which involved positive feedback as a prior art. His earlier relevant patent[44] seems to have been filed in December 1913, and this covers what later became known as the autodyne method of reception, using a feedback valve circuit for the local oscillator. His claims do not involve the feedback, but only the method of reception and the circuit detaii. A somewhat later patent[45] includes a feedback oscillator as part of a transmitter.

4.10. *Conclusions regarding the Invention of Positive Feedback in Electronic Circuits*

From the account of the work of the various inventors given above, it seems reasonable to conclude that:

(a) The self-oscillating audion was discovered in late 1911 by Lowenstein.

(b) The fact that feedback could produce oscillation in an audion was discovered by Van Etten in August 1912.

(c) The *use* of feedback as such was invented early in 1913 by Armstrong, Reisz, Meissner and Franklin, all within a month or two of one another.

(d) The concept of feedback affecting the damping of the resonance and sharpening the tuning was due to Franklin in 1913.

It is interesting to speculate on the soundness of the principles of law which led to the award of the priority (and hence profits) of invention to de Forest who did not 'invent' feedback (although his assistants may have done so in a limited sense) and who did not understand, exploit or patent the principle until long after several others did understand, did exploit and did patent it.

5. Self-oscillating Detectors: Autodyne and and Homodyne

In the development of feedback amplifiers and oscillators, some special properties and advantages of oscillating receivers were noticed and developed. These followed the ideas of heterodyne reception, which had been invented by R. A. Fessenden in 1902[46] but not used extensively in pre-audion days. The burst of new development produced by the valve circuits led to a great deal of concurrent theoretical analysis of heterodyne reception[47–50] and before long to the invention by Armstrong [51] of the 'superheterodyne' (as it later became called) in which a signal which is of too high a frequency for direct amplification is changed to a lower frequency where amplification can readily be provided. However, the oscillating receivers to which reference was made above are the *autodyne* and the *homodyne*—to use names which were introduced a little later.

The autodyne may be defined as a receiver in which self-oscillations are generated at a frequency different from that of the incoming signal; these oscillations heterodyne with the signal in the non-linearity of the receiver to give a beat (or 'heterodyne') tone at a convenient frequency. The system was used basically for radio-telegraphy, and the beat tone was thus in the audio range, to be heard on headphones.

The homodyne may be defined as a receiver in which self-oscillations are generated at the same frequency as that of the incoming signal; provided the phase-relationships are correct, interaction in the non-linearity of the receiver gives an audio output corresponding to the modulation on the incoming signal. This system is therefore useful for receiving speech transmissions.

5.1. *The Autodyne*

As with the basic concept of positive feedback, so with the autodyne there was a spate of patents from different inventors all at more or less the same time—in this case, however, even more closely spaced.

The autodyne depends, of course, on the receiver having a continuous self-oscillation to beat with the incoming signal. It is clear, therefore, that the development of the autodyne was dependent on not only the audion valve itself, but also on feedback to make it oscillate. It is thus particularly interesting that the basic idea of the autodyne was first put forward, by H. J. Round,[52] in terms of a circuit which not only had no feedback but also had no audion! The basic circuit of this is shown in Fig. 5; here C is a crystal rectifier. The aerial is out-of-tune with the incoming waves by a frequency difference f, say. Circuit B is 'preferably aperiodic'. Each burst of signal (telegraphic) excites a transient oscillation in the input tuned system of frequency equal to the natural frequency of resonance, i.e. at a frequency differing from the signal by f. The rectifier therefore produces a beat note of f, and circuit D is tuned to f so that a tonal pulse of this frequency is heard in the telephone receiver.

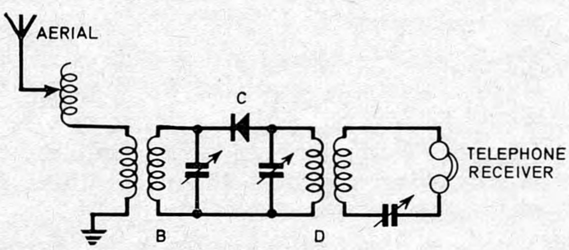


Fig. 5. Round's anti-atmospheric receiver showing the principle of the autodyne.

Marconi photograph

Mr. Charles S. Franklin, C.B.E., (1879–1964) and Captain Henry J. Round, M.C., (1881–1966). Taken in 1962 during the making of a film on their contributions to radio engineering.

Round's object in designing this system was to provide immunity from 'atmospherics' which comprise bursts of interference of very short duration. The idea is that such interference cannot produce the beat tone f of sufficient duration to be recognized as a tone in the telephone receiver. But Round says that 'with such a simple arrangement however it may be difficult to get the beat frequency unaffected by atmospherics and yet low enough to be within the limits of audibility' and so he proposed that the frequency difference f be made considerably greater, and a second heterodyne stage be provided to change *f* down to an audible frequency, using a local oscillation generator of unspecified type.

The first autodyne using a valve to produce a continuous local oscillation was also due to Round and was mentioned earlier in Section 4.9. It was patented[53] only a few days after the system just described; the basic circuit is shown in Fig. 6. Here the tuned circuits A and E are tuned to slightly different frequencies, and by varying the coupling between them, the self-oscillation may be produced at a frequency suitable for producing an audible beat-note in the telephone receiver.

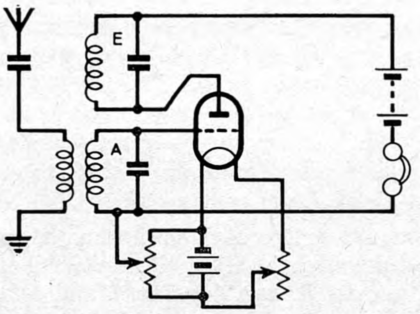


Fig. 6. Round's autodyne receiver.

Round's system was closely followed by a patent by Armstrong[54] only nine days later covering substantially the same idea, except that Armstrong used his preferred method of obtaining feedback by connecting the telephone receiver as a common impedance between anode and grid circuits.

Meissner's patent,[55] already referred to in Section 4.7, includes, among other uses of positive feedback, not only the autodyne receiver, but also a double or reflex autodyne receiver which uses the autodyne principle for both radio-frequency and audio-frequency stages in one and the same valve!

Both Armstrong and Meissner refer to the increased sensitivity of the autodyne system (although they do not use that name for it).

As with positive feedback itself, de Forest enters the autodyne patent scene rather later than the others. The patent[28] of March 1914 by himself and C. V. Logwood shows what seems to be an autodyne receiver, but the explanations are not clear. In an article[56] early in 1915 he describes what is clearly an autodyne under the name 'ultraudion'. The sub-title is significant: 'Modification of the audion which makes of it an extraordinary sensitive instrument for this purpose and offers great possibilities for high-speed wireless records'. The audion is made to oscillate by overheating the filament, it is tuned to be slightly different from the incoming frequency, and the sensitivity is then claimed to be increased by a factor of from 10 to 50. But there is no science here, no explanations.

De Forest gives a more personal account of his invention of the ultraudion in his autobiography[57] and describes how it came to be made.

5.2. *The Homodyne*

It is difficult to think that the homodyne could ever have been a true invention, because the autodyne would obviously have become one whenever the self-oscillation pulled in or synchronized to the incoming signal. However, so long as the autodyne was used only for receiving telegraph signals (which was all it was suited for) this synchronized condition would have been an undesirable nuisance, a condition to be avoided. As Armstrong said in his patent already cited:

> 'So long as the oscillations thus generated in the detector circuit are of the same frequency as the received oscillations no signals will be heard in the telephones....'

He also referred to the need for the coupling between the aerial and the receiving circuit to be extremely loose, probably to avoid pull-in of the oscillation.

Presumably what inventive process there was in the concept of the homodyne lay in the appreciation that it could efficiently demodulate a carrier wave modulated by speech. This seems to have been realized first by by Burton W. Kendall[58] in 1915. It is possible that he approached the invention rather from the point of view that increased sensitivity could be obtained in a receiver if a local carrier were added to reinforce the incoming wave, for this is the first thing mentioned in his specification; but he quickly goes on to describe the self-oscillating detector, which was then the only practicable form of the system. The appropriate circuit arrangement from his specification is shown in Fig. 7.

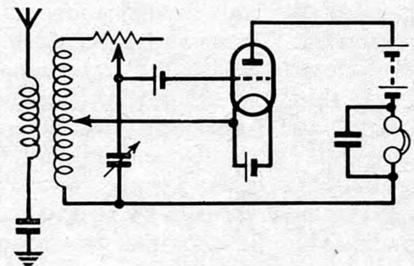


Fig. 7. Kendall's homodyne receiver of 1915.

The homodyne, unlike the autodyne, was the subject of much interest and development later. In 1923, Hartley[59] gave a mathematical discussion of the subject, showing the effect of phase errors in the local oscillation, etc. In an article in 1924 Colebrook[60] described the homodyne substantially as Kendall specified it. From about this time onwards, however, the system developed towards one of greater refinement, with the non-linear oscillation circuit separated from the desirably-linear signal circuit; the name 'synchrodyne' was later coined by the present author. The history of this development from the early 1920s onwards has been separately published[61] and will therefore not be pursued here.

6. Super-regeneration

In addition to the autodyne and homodyne there were many other circuits and systems developed which utilized positive feedback. Many examples are summarized in Blake's book.[4(a)] Here we shall confine ourselves to what was almost certainly the most important—the super-regenerative receiver.

The name was given to the system by Armstrong, who is generally held to be the inventor. It is, however, difficult to see the difference in principle between Armstrong's system[62,63] and the considerably-earlier British one due to J. B. Bolitho.[64,65] A somewhat similar principle was involved in L. B. Turner's 'valve relay'.[66] The general idea is to exploit the extremely high gain which is obtained in a feedback valve circuit which is just on the point of oscillating. At this point, the application of the signal, even of almost infinitesimal magnitude, will produce a substantial amplitude of the oscillation, and this amplitude will depend on the signal amplitude. The problem is, of course, that a valve circuit cannot normally be held just at the point of oscillation. It is normal for the amplitude to build up until limited by non-linear action, at which point the extreme sensitivity to the applied signal has been lost. So the object of all these super-regenerative inventions is to keep the circuit just at the point of oscillation.

This object is achieved by using an auxiliary circuit such that as soon as the oscillation starts to build up it is quenched by a brief alteration of a parameter of the circuit; it then starts to build up again, and so on. If the quenching is caused to occur at intervals which are too close to cause any audible modulation of the output audio signal, but which are sufficiently spaced in relation to the cycles of the radio signal, then the envelope of the oscillation waveform reproduces the modulation (audio) signal with extremely high amplification and usually acceptable distortion. Turner used an electromechanical relay to short-circuit the feedback as the oscillation built up, but this was obviously inadequate for speech. Bolitho and Armstrong used separate valve oscillators to give the periodic quenching, the former by causing the feedback to be largely cancelled as the separate oscillator went through its positive half-cycles, the latter by applying the output of the separate oscillator to the grid of the feedback valve, so that the amplification was cut off on negative half-cycles of the separate oscillator. One of Armstrong's circuits is shown in Fig. 8. Here the circuit A is the radio-frequency amplifier and detector, and circuit B is the separate oscillator of lower frequency.

There were many other versions of the super-regenerative receiver, one even using gas-flames as oscillating grid leaks,[67] and some of these are summarized in Blake's book already cited.

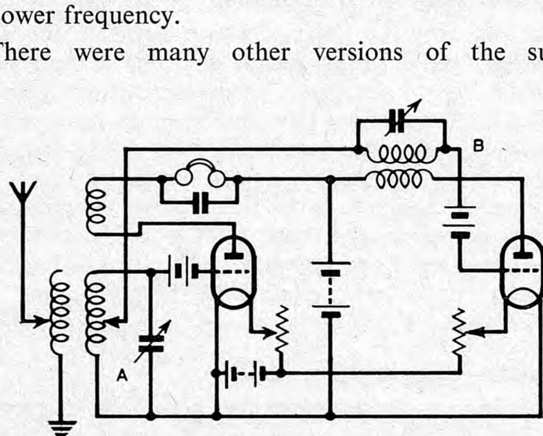


Fig. 8. Armstrong's super-regenerative receiver.

7. The Non-linear Theory of Oscillators and Synchronization of Oscillators

With the increasing use of oscillating electronic circuits, it was to be expected that theoretical and mathematical studies of oscillators should be undertaken. The first of these appears to be a paper by Hazeltine[68] in 1918, which is a very thorough and admirable study, introducing the useful concept that positive feedback is equivalent to a negative resistance, but dealing mathematically with the circuits in purely linear-circuit terms. In his discussion of the behaviour of oscillators in respect to the incoming signal to which they may be coupled in an autodyne circuit, he describes what appears to be the pull-in effect (later called synchronization of oscillators) but his account is not satisfactory on this matter, nor is he (naturally) able to analyse it properly with his linear representations.

The recognition that the non-linear characteristic of the valve dominates the study of oscillating circuits was probably due to B. van der Pol,[69] and another early study was made by E. V. Appleton,[70] partly in collaboration with van der Pol. Synchronization of oscillators was recognized as part of this non-linear behaviour.[71, 72]

Subsequent work in this field has been prolific and need not be discussed further here.

8. Conclusions

We have now traced the history of positive feedback from its origins up to the early 1920s. It can be seen that the topic played a vital part in radio development from about 1911 or 1912 onwards, and that numerous nventors were almost simultaneously, and usually competitively, 'inventing' the same thing at each stage. We have made some sort of judgement on the priorities (in a technical rather than legal context) in the basic inventions of positive feedback in electronic circuits, and these give no place to de Forest, who nevertheless was awarded priority by the U.S. Supreme Court.

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Manuscript received by the Institution on 19th July 1971. (Paper No. 1433/CC 118).

LETTERS

The History of Positive Feedback

In his most interesting article on 'The History of Positive Feedback', Professor Tucker says of the Autodyne 'that it was only used for receiving telegraph signals (which was all it was suited for)'.

A few months ago I dismantled the last of several regenerative receivers, designed and built by myself around 1931, which were all used for broadcast reception. A total of five valves was used, the first an autodyne frequency changer feeding a steerable i.f. amplifier and with a second detector fitted with switchable super-regenerative circuits. The receivers were very sensitive and easy to operate and it was possible to listen to American broadcasting on most days. When ionospheric conditions permitted, the police cars touring around the streets of Chicago and New York were a part of my regular listening.

MICHAEL LEESTON-SMITH
T.Eng.(CEI), (*Associate*).

9 Sandpits Road,
Petersham,
Richmond-on-Thames,
Surrey.
20th March 1972.

In Professor Tucker's paper the word 'autodyne' is chiefly used to describe a self-oscillating detector which is intended for c.w. reception; that is, so that an audio-frequency beat note is produced. One sentence, (p. 76, Section 5, 2nd para) however, suggests that it applies also to the case of a much higher beat frequency.

I do not myself remember 'autodyne' being commonly used for a self-oscillating detector. I fancy its use was dying at the time when I was first getting seriously interested in radio (about 1925). What I do remember is that 'autodyne' was used for a single-valve frequency changer in a superheterodyne; it was usually called an autodyne frequency changer.

Mr. Leeston Smith's receiver employed an arrangement which was sometimes adopted to prevent radiation of the quench frequency.

W. T. COCKING
C.Eng., F.I.E.E.

29 Arundel Avenue,
East Ewell,
Surrey.
18th April 1972.

I am grateful to Mr. Cocking for adding his experiences of early superheterodyne receivers to Mr. Leeston Smith's interesting recollections. It seems that the term 'autodyne' originally used for a self-oscillating c.w. heterodyne device, became transferred to a single-valve frequency-changer performing almost identically the same function.

D. G. TUCKER
D.Sc., C.Eng., F.I.E.E., F.I.E.R.E.

Department of Electronic & Electrical Engineering,
The University of Birmingham,
P.O. Box 303,
Birmingham B15 2TT.
2nd May 1972.

Professor Tucker's paper throws light both on the technical background to the technique of positive feedback and on the patent litigation which often follows an invention. In connection with the latter some observations by Professor E. H. Armstrong following the final Supreme Court decision add an interesting postscript which may well be new to many readers.

The American magazine *Electronics* of June 1934 had said:

'The amount of money that has gone into this fight must run to several millions of dollars; so far as the art was concerned, wasted, gone to attorneys and patent lawyers instead of being reinvested in further research to the benefit of the art . . . So far as recognition goes, both de Forest and Armstrong are appreciated as inventors of the first rank—the only regret is that their energies could not have been spent exclusively in invention and not futilely dissipated in litigation'.

Armstrong's reply in a letter to W. R. Maclaurin (quoted in the latter's book 'Invention and Innovation in the Radio Industry', Macmillan, New York, 1949) was as follows:

'There is one comment that might be made with respect to the editorial in *Electronics* and that is in respect to the words "not futilely dissipated in litigation". The whole proceeding may appear on the surface to have been a futile one but a man's destiny sometimes moves in a very strange way. Because of the circumstance that a patent attorney on the other side made a statement in the regenerative circuit case that wasn't true, and because I had the burden of setting up apparatus to prove what the truth was, I accidentally ran into the phenomenon of super-regeneration. The sale of that invention a year later was to net me more of a return than the sale of the regenerative circuit and the superheterodyne combined. It was that invention (super-regeneration) which furnished, in fact, the resources by which I was able to continue my investigation of the problem of static that was to lead to the development of frequency modulation. I would never have made the super-regenerative invention had I not been engaged in the regenerative circuit litigation'.

Perhaps Armstrong's experience will provide a ray of encouragement to the many other inventors whose expectations may seem to have been dashed to pieces in the law courts!

F. W. SHARP
C.Eng., F.I.E.R.E.

65 Priory Road,
Cheam,
Sutton, Surrey.
12th May 1972.

Letters commenting on published papers or putting forward other matters of technical interest are invited by the Editor for consideration for publication. Longer letters will normally be regarded as 'short contributions' and will be dealt with in the same manner as submitted papers with an accelerated refereeing process.