Introduction to "Stabilized Feed-Back Amplifiers"

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Invited Paper

Harold L. Black's Classic Paper "Stabilized Feed-Back Amplifiers" appeared five years after he invented the feedback amplifier and four years before the patent was finally issued. Black's paper shows the advantages of negative feedback in reducing harmonic distortion, increasing the bandwidth, and maintaining robust performance using primitive vacuum tubes. It also introduces a nomogram similar to the well-known Nichols Chart. In an effort to gain a better understanding of the unerlying mechanism of feedback, he enlisted the aid of H. Nyquist who responded with his famous paper, "Regeneration Theory."

Keywords—*Feedback, feedback amplifiers, history.*

Harold L. Black (Fig. 1) invented the feedback amplifier onboard a ferry boat to New York on August 6, 1927. The disclosure for this invention was hand sketched by Black, and duly witnessed, on a page of the *New York Times*. All this is part of the folklore of electrical engineering.

The chronology of this invention and collateral developments is revealing and has much to teach about the history of electrical engineering in the twentieth century:

August 1927—Black invents the feedback amplifier;
August 1928—Black files for patent on feedback amplifier;
July 1932—Nyquist publishes classic paper on "Regeneration Theory";
January 1934—Black publishes classic paper "Stabilized Feedback Amplifiers";
December 1937—U.S. Patent 2 102 671 for Black's feedback amplifier is granted, nine years after filing date.

The principle of using the difference between the desired output of a system and its actual output antedates negative feedback in electrical amplifiers by about a century. This is the principle of operation of Watt's ball governor of the early nineteenth century. It was studied extensively in the nineteenth century by Maxwell and other luminaries and led Routh to the development of his celebrated algorithm for determining whether a polynomial has roots in the right half of the complex plane, already well known to be the requirement of instability. But this principle was not identified as feedback, a term that appears to have been invented by radio engineers around 1920[1] and hence not recognized by them as being relevant to radio receivers and telephone amplifiers.

Black could not have been expected to appreciate the significance of the nineteenth-century work on stability

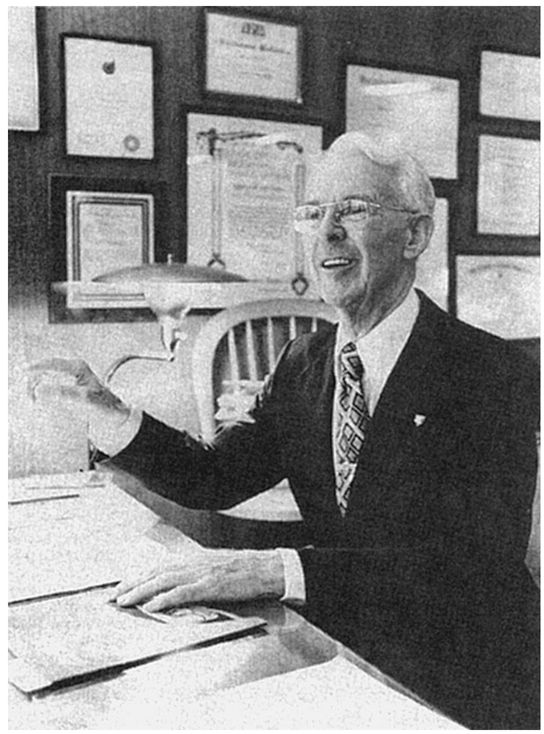

Fig. 1.

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[1] The term "feedback" appears to have been used in describing the regeneration process in radio receivers of the era. The term "negative feedback" may have been originated by Black.

of mechanical systems. With only a B.S. degree (from Worcester Polytechnic Institute) and having pursued the traditional electrical engineering curriculum of the early twentieth century, it is unlikely that he was even aware of this work. Black wrote of his admiration of Steinmetz (whose numerous contributions to electrical technology included the introduction of complex numbers for the analysis of electrical networks in the sinusoidal steady state), but like other electrical engineering students of his time, he apparently was not exposed in his engineering studies to mathematics much beyond high-school algebra. Recognizing that the stability of feedback amplifiers depended on the frequency dependence of the amplitude and phase shift through around the feedback loop, and aware of his own limitations in mathematical analysis, he enlisted the aid of his Bell Laboratories colleague, Harry Nyquist:

> When first thinking about this matter it was suspected that owing to practical nonlinearity, singing [sic] would result whenever the gain around the closed loop equalled or exceeded the loss and simultaneously the phase shift was zero; .... Results of experiments, however, seemed to indicate something more was involved and these matters were described to H. Nyquist who developed a more general criterion for freedom from instability ... [1].

Nyquist's magnum opus [2] appeared in 1932, after Black invented the feedback amplifier but before Black's paper on its theory appeared.

Nyquist was also trained as an electrical engineer, but, unlike Black, he had a Ph.D. degree (in physics, from Yale University). His work at Bell Laboratories was concerned with the use of complex variable theory in the analysis of linear electric circuits and provided the background appropriate for the analysis of feedback systems. Yet, notwithstanding the comprehensive and elegant analysis of Nyquist's paper, one has the feeling that he did not fully appreciate the significance of Black's contribution at the time. Nyquist's paper does not even acknowledge that it was Black's feedback amplifier problem that motivated his investigation. The title of Nyquist's paper, "Regeneration Theory," suggests that positive feedback (i.e., regeneration) is the important phenomenon:

> Regeneration or feed-back is of considerable importance in many applications of vacuum tubes. The most obvious example is that of vacuum-tube *oscillators* ... [2, emphasis added].

Positive feedback to sustain oscillation was fairly well understood by radio engineers. Armstrong's regenerative receiver, invented in 1920's, used this principle which was known in Germany early in the century through the work of Barkhausen on oscillators.

Black was not interested in sustaining oscillations, of course, but in avoiding them while achieving his goal of remedying problems in designing amplifiers constructed with the relatively primitive vacuum tubes of the 1920's. Without vacuum tubes, long-distance constructed telephone communication would have been all but impossible. By means of vacuum tubes, however, the telephone signals that had been distorted and attenuated by the transmission lines could be amplified at "repeater" stations and thereby transmitted for long distances. The tubes of the day, however, in addition to being nonlinear, had uncertain characteristics. It was thus not possible to accurately predict how an individual vacuum-tube amplifier would behave. Black recognized that by using an amplifier comprising several vacuum-tube stages in cascade to yield a very high open-loop gain, and then "killing" most of the open-loop gain by using a large amount of negative feedback, the resulting "negative feedback amplifer" would be virtually insensitive to nonlinearity and uncertainty in the characteristics of the vacuum tubes.

Since the vacuum-tube amplifier stages had to be coupled through capacitors (then called "condensers") to isolate the dc power supply of one stage from the input to the next, and the large vacuum tubes had significant interelectrode capacitances, the bandwidth of the typical vacuum tube amplifier was rather narrow. Black showed that the use of negative feedback had the very beneficial effect of increasing the bandwidth of the resulting amplifier.

Black recognized that one expression, in his notation

$$\frac{1}{1-\mu\beta}$$

where μ is the forward transmission and β is the feedback transmission explained all the benefits of negative feedback. Note that Black retains the custom of the period of using a minus sign in the denominator of the function now recognized by control engineers as the "sensitivity function."

Nomograms and other graphical analysis tools were popular with engineers in the precomputer era. To assist in the analysis of the closed-loop sensitivity function, Black devised a chart with the magnitude of the loop transmission $|\mu\beta|$ as the abscissa and the of the phase of $\mu\beta$ as the ordinate. By means of this chart, the user could determine the magnitude and phase of the sensitivity function. Black's chart (see [1, Fig. 4]) anticipates the famous Nichols Chart [3]. The Nichols Chart differs from Black's chart in that the former displays contours of the closed-loop transfer function, in Black's notation

$$\frac{\mu\beta}{1-\mu\beta}$$

rather than of the sensitivity function. In addition, the axes of the former are rotated 90° and the magnitude is expressed in decibels.

Black's paper [1] also exhibits what may well be the first experimentally obtained Nyquist diagrams for feedback amplifiers, one stable and one unstable when the loop is closed. Interestingly, he plots the magnitude $|\mu\beta|$ of the loop transmission in decibels, thus using a logarithmic radial scale. How the case of zero gain ($-\infty$ dB) would be handled with this scale is not explained, nor do Black's Nyquist diagrams close on themselves.

At the time of its publication, the signficance of Black's seminal paper was not fully appreciated by the gatekeepers of the American Institute of Electrical Engineers (AIEE) publications. At the time, the AIEE published two series of publications: the *Transactions of the AIEE* and a journal (also confusingly subtitled "Transactions") *Electrical Engineering*. The former published serious, scholarly papers; the latter published more "popular" papers as well as meeting notices, minutes of committee meetings, and similar news items. Significantly, Black's paper appeared in *Electrical Engineering*, not in the *Transactions of the AIEE*. Perhaps the reviewers and the editors were uncomfortable with ideas that were not developed to the customary level of mathematical rigor. *Plus ça change, plus c'est le même chose*.

Black's invention was radical and counter intuitive. Why would any reasonable engineer build a multistage amplifier with costly and unreliable vacuum tubes, only to reduce the gain of the amplifier by a factor of 10 000 or more? Black's idea is now of course commonplace (serving, for example, as the basis of the "operational amplifier" invented—reinvented?—in the 1940's and part of the stock in trade of all analog circuit designers). At the time, however, Black's supervisors did not share his conviction. Black writes of his director of research:

> He [the director of research] insisted that a negative feedback amplifier would never work. I don't know the reason behind his doubts; possibly they arose from his training as a physicist [4].

According to Black, the patent office similarly failed to recognize the significance of negative feedback and took over nine years to decide to issue the patent:

> . . . the concept was so contrary to established beliefs that the Patent Office initially did not believe it would work. The Office cited technical papers . . . that maintained the output could not be connected back to the input unless the loop gain was less than one . . .. In England, our patent application was treated in the same manner as one for a perpetual motion machine . . .. The British patent office . . . asked me to submit a working model! [sic] [4].

Black's invention worked, of course. In his Classic Paper [1, Fig. 2] Black exhibits the schematic diagram of a negative feedback amplifier comprising two pentodes and a tetrode, and including the bridge circuits (at the input end and at the output end), as illustrated in the sketch he drew on the *New York Times* of ferryboat fame, that he devised to achieve the required negative feedback. These amplifiers were field tested in Morristown, NJ, prior to the publication of the paper. According to Black, "[t]he results of this trial were highly satisfactory and demonstrated conclusively the correctness of the theory and the practicability of its commercial application [1]."

Ironically, Black's role in feedback theory is all but forgotten. In Bode's classic 1945 work [5] his contribution is relegated to a single footnote. Black's own later efforts were directed elsewhere. He is best remembered for his work on modulation theory [6].

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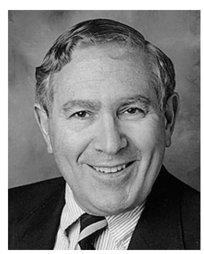

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