Development of the PID Controller

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In 1939, the Taylor Instrument Companies introduced a completely redesigned version of its "Fulscope" pneumatic controller: this new instrument provided, in addition to proportional and reset control actions, an action which the Taylor Instrument Companies called "pre-act." In the same year the Foxboro Instrument Company added "Hyper-reset" to the proportional and reset control actions provided by their "Stabilog" pneumatic controller. Pre-act and Hyper-reset actions each provided a control action proportional to the derivative of the error signal. Reset (also referred to as "floating") provides a control action proportional to the integral of the error signal and hence both controllers offered PID control.

Of the two instruments, only the Fulscope provided for full field adjustment of the controller parameters; the Stabilog had to be set to one of four fixed settings of the derivative-plus-integral term in the factory, the proportional band (gain) of the controller could be adjusted in the field. Field adjustment did, however, pose a problem since there was no established method of choosing the appropriate settings for each of the three terms of the controller. Recognizing this as a weakness, the Taylor Instrument Companies carried out extensive investigations in an attempt to devise ways of choosing optimum control settings for the PID controller. The outcome of this work was two papers by J.G. Ziegler and N.B. Nichols published in 1942 and 1943 [1], [2]. In these papers Ziegler and Nichols showed how optimum controller parameters could be chosen based first on open-loop tests on the plant; and second on closed-loop tests on the plant.

In the immediate post-war period other instrument companies introduced three-term controllers, and the analog two- and three-term controllers became the primary control mechanisms for a wide range of industries. The Ziegler and Nichols methods for tuning the controllers have continued to be used, although following work by G.H. Cohen and G.A. Coon of the Taylor Instrument Companies during the 1950s, alternative choices of parameters have been become accepted for certain types of plants [3].

Early Process Control Devices

Feedback devices that could control liquid levels and flows were known to the Hellenic Greeks; accounts of isolated attempts to provide speed regulation are found in late medieval literature. In the mid-seventeenth century, Cornelius Drebbel experimented with a feedback system for the control of temperature in a furnace.[1] Conceivably, all these devices could have been applied to the control of manufacturing processes; however, it was not until the eighteenth century that serious attempts were made to translate ingenious ideas into effective industrial control devices. By the end of that century, position control devices — the fantail mechanism for keeping a windmill pointing into the wind and the lift tenter for regulating the gap between grinding stones — were increasingly being used. James Watt modified the lift tenter to form the flyball governor which, when connected to a throttle valve (another Watt invention), provided speed control for the steam engine (see [4]-[6]).

During the nineteenth century, the Watt engine governor was widely adopted and there were thousands of patents for new and modified forms of engine governors, few of which saw actual use [7]. During this century there also was an enormous range of inventions for temperature, pressure, and flow control devices. The overwhelming majority of such inventions were for "direct controllers;" that is, for devices in which the measuring element was directly connected to the control actuator and hence the force available to operate the actuator was dependent of the force that the measuring device could develop. By the end of the 19th century, regulators of this type were in widespread use.[2]

During the latter years of the nineteenth century and the early part of the twentieth, complex changes took place in the organization of industry in the United States [9], [10]. These changes led to an increased demand for devices for recording information relevant to production processes — from simple records of when a machine was turned on and off; to records of temperatures, pressures and flows for food processing plants, chemical works and steel works; and to records of steam pressure and carbon dioxide per-

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[1] For an account of these early attempts at feedback control see [4].

[2] Reference [8] gives the only full account of direct acting controllers.

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centages in power stations. The desire for accurate recording devices directed attention to the problem of connecting a mechanism for moving a pen across paper to a measuring instrument without loading the instrument to such an extent that the measured value was distorted. The pressure operated recorders of William H. Bristol, which were based on using a modified form of the Bourdon tube, set the standard for mechanically operated devices;[3] the Callendar recorder of the Cambridge Scientific Instrument Company set the standard for potentiometric devices, although this was largely a laboratory instrument and potentiometric recorders were not widely used in industry until the introduction of the Leeds recorder by the Leeds & Northrup Company in 1912.[4]

Following the end of the first world war, there was rapid growth in the United States in the use of industrial instruments and the story of the development of the practical PID pneumatic controller is closely related to this rapid growth. Based on a U.S. Government survey published in 1935, I estimate that between 1925 and 1935, more than 75 000 automatic controllers were sold in the United States, and figures show that in 1935, 32% of the total sales of the American instrument manufacturers were automatic controllers [16]. The majority of these controllers were simple on-off devices but there was a growing realization that for many applications accurate control could not be achieved by simple on-off action.[5]

The controllers sold by the instrument manufacturers from about 1910 on can be divided into two major categories: electrical and pneumatic. The electrical controllers used relays which were used to switch on and off motors used to open and close valves or to position rheostats. A schematic diagram illustrating the principles of the devices is given in Fig. 1. The measured physical quantity (temperature, pressure, flow were the most widely required measurements) is converted into a mechanical deflection of a pointer. For example, by using an expansion thermometer, the pressure changes generated by a change of temperature cause the

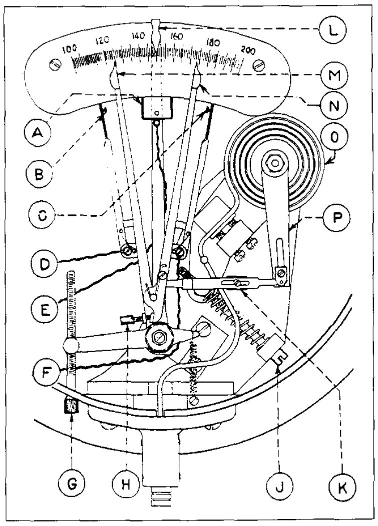

Fig. 1. A typical contact-operated electrical controller of the middle 1920s, reproduced from [44].

spiral wound tube O to rotate, thus moving arm P, and hence the pointers M and N. Placed either side of the pointers and attached to them are high and low contacts B and C. A center contact L marks the set point and when either B or C touches L an electrical circuit is made resulting in a relay closing. Electrical controllers of this type were simple and robust; however, they could not provide high precision since it was difficult to arrange for the contacts to have a small dead space. The dead space could be adjusted by changing the gap between M and N, and hence B and C. Claims were made that a dead space equal to 1% of full scale could be achieved but in reality it was difficult to achieve even 5%, and 10% to 15% was normally the best that could be achieved.

Pneumatic controllers were based on either the use of mechanical deflection to operate directly a pilot valve, which then controlled the operation of a diaphragm valve, or on the use of a flapper-nozzle amplifier to operate the pilot valve. Controllers based on direct operation of the pilot valve were simple to build, but attaining precise control was difficult: the force required to operate the pilot valve both loaded the transducer significantly and also varied nonlinearly with the valve movement. The introduction of the flapper-nozzle amplifier between the transducer and the pilot valve removed the loading problem but its high gain and nonlinear behavior increased the sensitivity of the system to such an extent that limit cycling could easily occur. The flapper-nozzle amplifier introduced by the Foxboro Company in 1919 had a proportional band of approximately 1%.

In addition to these two types of controllers based on using a measuring system that provided a mechanical movement, the potentiometric (null balancing) recorder also could be used to activate a controller. The null balancing method avoided any loading effects on the delicate galvanometer required for making thermocouple or resistance thermometer temperature measurements. At the turn of the century the Cambridge Scientific Instrument Company manufactured and sold some Callendar potentiometric recorders for industrial use; however, this recorder was essentially a laboratory instrument and after about 1912 was largely superseded for industrial use by the Leeds and Northrup Company's potentiometric recorder. The internal mechanism used in the Leeds recorder to achieve null balance provided a form of proportional action. At approximately one-minute intervals the galvanometer needle was clamped, mechanical sensing fingers detected the extent of the deflection of the needle from the desired null position, and a motor connected to the wiper arm of the bridge balancing circuit was run for a period of time proportional to the deflection from the null position. The position of the wiper arm is thus proportional to the measured quantity. In the recorder, the pen traced the movement of the wiper arm. It was a simple matter to operate a second motor connected to an external control valve. Fig. 2 shows a bank of Leeds & Northrup controllers being used for the control of temperature in hardening furnaces (about 1920).

The Leeds & Northrup Company called their controllers "proportional step" controllers; however, since the position of the control valve was determined by the sum of a series of integrations of the motor speed with respect to time it was a "floating" or "integral" controller. It would have given a zero steady-state error, but for stable operation the motor speed had to be low, and hence it responded slowly to load or set point changes. Morris E. Leeds, the founder of the Leeds & Northrup Company, obtained a patent in 1920 for an automatic controller whose rate of change of corrective action was specified as being a function of the rate of change of error, or of the error, or of a combination of the two.

[3] See [11] and [12]. The latter device incorporated a helically wound Bourdon tube devised by Edgar H. Bristol.

[4] For a general history of the development of these types of recorders see [13]. Specifically for the Leeds recorder see [14] and [15].

[5] For a detailed account of the developments see [17]. See also [18] and [19].

Fig. 2. A bank of Leeds & Northrup Company controllers installed in the hardening room of the Continental Motors Co., Muskegon, MI. The illustration is from [41].

application broader than just proportional [20]. The combined action when a proportional function is used gives PI control action. The difficulty was how to build a controller which would combine the two elements. It was not until the late 1920s that such controllers, based on the use of two motors with gears and mechanical linkage to combine the outputs, were produced. These controllers were referred to as definite correction mechanisms, that is, sampled data systems, and as such their behavior was difficult to analyze and predict.

Pneumatic Controller Development

The successful line of pneumatic controllers was based on the flapper-nozzle amplifier. Movement of the flapper arm towards or away from the nozzle causes a change of back pressure in the pneumatic circuit and this change in pressure results in a movement of the diaphragm bellows. This movement can be applied to a pilot valve which, in turn, controls the opening and closing of the main control valve. The basic flapper-nozzle mechanism was invented by Edgar H. Bristol of the Foxboro Company during the winter of 1913-1914. A patent application was filed in 1914 and granted in 1922 [21]. Initially, Bristol designed the pneumatic circuit to work under vacuum but ingress of dirt and dust into the narrow tubes led the Foxboro Company to switch to pressurized operation (hence, the pressure range 0 to 15 psi for pneumatic controllers). The basic flapper-nozzle mechanism is highly nonlinear, in the early versions of the Foxboro controllers the flapper-nozzle mechanism was used as an on-off relay. The gain of the flapper-nozzle was such that a change in the measured quantity equal to 1% of full scale of the measurement would cause 100% change in the back pressure. The early controllers had a very simple construction as shown in Fig. 3. The cam mechanism which can be seen in the center of the picture was used to adjust the set point.

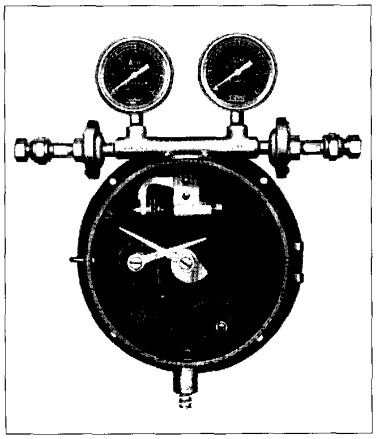

Fig. 3. A simple Foxboro Company pneumatic controller. The controller was introduced in about 1922. Reproduced from [42, p. 16, fig. 2322].

Throughout the 1920s all the companies manufacturing pneumatic controllers attempted to increase the range of linear operation of all the components in the system. In 1927 Foxboro introduced a controller with a proportional band of between 5% and 7% of the full scale measurement. This was achieved by modifying the flapper-nozzle arrangement such that the flapper and nozzle approached each other at a small angle and thus closed off the air at a more gradual rate. This controller is illustrated in Fig. 4. The flapper mechanism is hidden behind the pen arm (the device illustrated is a combined recorder-controller) and the pilot valve (16) is separated from the flapper arm.

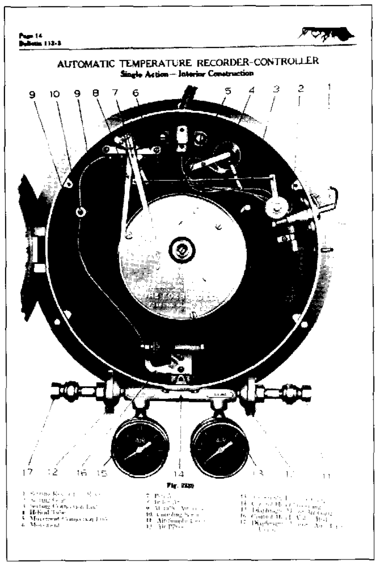

Fig. 4. A Foxboro Company pheumatic recorder-controller of about 1929, reproduced from [42, p. 14].

In practice, because of the problems caused by the high gain of the controllers many of the instrument manufacturers recommended using bypass control schemes. In such schemes the controlled medium, for example, steam used for heating, is split into two parts, one controlled by the automatic device and the other, the bypass, controlled by a manually set valve. Large changes in loads or in set-points are accommodated by adjusting by hand the bypass valve.

In the late 1920s, the Taylor Instrument Companies claimed that by careful design of the pilot valve (at this time they did not offer controllers which used the flapper-nozzle amplifier) they could achieve proportional action in excess of 5% of full scale. The Foxboro Company seemed to be concerned that the growing interest in "throttling" control, that is, proportional control, during the late 1920s might threaten its market for the flapper-nozzle threaten its market for the flapper-nozzle based controllers. In one of its bulletins issued in 1929, the company argued that "close limits of control must be sacrificed, if throttling action is desired when the process is out of balance." The company also was working on finding ways of modifying its controllers to increase the proportional band. On August 14, 1928, two patents for pneumatic process controllers were filed by Foxboro employees, one by Clesson E. Mason and the other by W.W. Frymoyer [22], [23]. Both devices used diaphragm units interconnected by capillary tubes to modify the back pressure signal in the flapper-nozzle unit. Frymoyer's device was the simpler of the two: the relationship between the output pressure P of the flapper-nozzle system and the input position X of the flapper is

$$p = Kx/(1 + TD)$$

where p and x represent small changes in P and X, K and T are constants, and D is the operator d/dt. For the mechanism proposed by Mason the relationship is

$$p = Kx(1 + aTD)/(1 + TD)$$

where a is a constant. If $a<1$, then Mason's device is a phase lag network and as such has the effect of reducing the gain at frequencies greater than $1/T$. A system based on Mason's invention was built and installed in an oil refinery; it is claimed that it gave good control; however, the diaphragm units kept fracturing due to repeated flexing and the system had to be removed.

During this period Mason also was working on the problem of producing a control valve in which the flow was proportional to the diaphragm pressure. His work led to the Foxboro V-port (Stabilflo) valve. In September 1930, Mason filed another patent application for a pneumatic control mechanism [24].[6] The basic idea of this invention is that there is feedback from the outlet of the pilot valve, that is the actuating signal for the control valve to the flapper nozzle. The feedback signal is modified by a pneumatic network such that the overall effect is to make the manipulated variable proportional to error and the integral of error. This mechanism was incorporated in the Foxboro Model 10 Stabilog controller announced in September 1931. Initially the Stabilog did not sell in large numbers: the users needed educating. The Foxboro Company relaunched it in 1934 and produced a brochure which explained in detail how it operated and the benefits to be gained from its use. The principles of its operation were explained using the diagram shown in Fig. 5. This diagram clearly shows the feedback connection from the "differential pressure motor" to the nozzle of the flapper valve. A key element in the success of this controller was the use of the recently developed "Hydron" welded steel bellows for the differential pressure motor. These bellows were able to withstand repeated flexing.

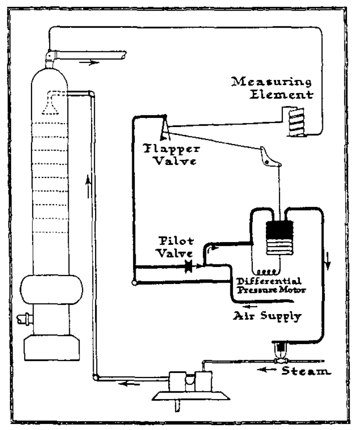

Fig. 5. A schematic diagram illustrating the principle of the Stabilog controller, reproduced from [43].

Rival companies were quick to see the benefits of the new control method: the Taylor Instrument Companies brought out its so called "Dubl-Response" unit which offered $P + I$ control in 1933 and the Tagliabue Company responded in 1934 with its "Damplifier" controller. The Taylor Instrument Companies challenge was the most significant as the "Dubl-Response" unit incorporated a feedback link from the position of the main control valve, hence including all of the controller components within the feedback loop.

By 1936, pneumatic controllers were available with a range of different feedback linkages: feedback around flapper-nozzle and pilot valve; feedback just around the pilot valve; and feedback around flapper-nozzle together with a separate loop around pilot valve and main control valve.

Derivative Action

During the 1920s there was much discussion of the need for a controller to act so as to anticipate an increase in the error and there were a variety of proposals to make the controllers respond to a rate of change in the measured variable. Most schemes, however, did not provide derivative control action since the actuating mechanism introduced an integral term. The so-called anticipating control resulted in the controlled variable being made proportional to the error. This did give a faster response since it replaced controllers in which the controlled variable was proportional to the integral of the error. True derivative control action resulted from work being carried out by the Taylor Instrument Companies on the control of part of the rayon making process. Mechanical working of the cellulose "crumb" results in both the generation of heat and a change in the cellulose from solid lumps to a fluffy consistency. The process requires that the temperature be maintained constant. Cellulose in its fluffy form is a good insulator and this resulted in increasing the effective time constant of the temperature transducer. With $P + I$ control the system oscillated. When given this problem, Ralph Clarridge of the Taylor Instrument Companies remembered that when he experimented with introducing a restriction in the feedback line of the proportional response controller, he observed a large "kick" in the response when the setpoint was suddenly changed. The controller was "anticipating" the change in the error signal. He decided to try this restriction on the cellulose plant controller; the system was tested on March 20, 1935, and found to work. The Taylor engineers named the effect "pre-act."[7] Until the fully redesigned Fulscope controller was introduced in 1939, the Taylor Instrument Companies installed pre-act as a special order when their engineers thought it appropriate to do so.

The Foxboro Company response to pre-act, which they called "hyper-reset," was developed during 1937-1938 and was the work of George A. Philbrick. During this period he also developed an electronic simulator. This was a hard-wired analog

[6] Leeds & Northrup argued that [24] infringed on Leeds Patent (1 332 182) of 1920 (see [25]), but I have not been able to establish if they pursued any infringement action.

[7] J.G. Ziegler gives an account of the invention of the "pre-act" in an unpublished memoir; an account is also to be found in [26].

contain up to four time lags and the controller could be configured as P, PI, or PID.[8]

Development of a Theoretical Understanding

Writing in 1933, A. Ivanoff commented "the science of the automatic regulation of temperature is at present in the anomalous position of having erected a vast practical edifice on negligible theoretical foundations" [27]. While Ivanoff's statement is true, we should not be led into thinking that the "practical edifice" had no foundation: it was constructed on what we would call "intelligent control;" that is, on heuristic control based on observation of the human operator.[9] Inventors such as Morris E. Leeds and Elmer Sperry (and many others) had an intuitive understanding that on-off and proportional control actions would not provide, in general, adequate control: they observed the actions that human operators took and in particular saw that the human operator both anticipated the buildup and reduction of error, and also compensated for a persistent error. In his address to the Newcomen Society of America in 1958, I. Melville Stein, who joined the Leeds & Northrup Company in 1918, claimed that, in 1912, Morris Leeds opposed coupling the Leeds & Northrup recorder to on-off controllers as he did not think that it would give satisfactory control. He argued that a controller needs to take into account all the factors that a good operator does [29].[10]

Similarly, Sperry built into his autopilots for ships and aircraft functions which mimic the behavior of the human operator. The complex mechanical arrangements used to generate the functions were difficult to analyze, and hence it was not clear what was the exact control action.[11]

During the 1920s and early 1930s, many engineers attempting to automate the control of process plants realized that on-off control could not always provide the stability and accuracy necessary for good control. They followed a path of development which led first to trying to make the control signal proportional to the error signal, and then introducing floating or integral action to compensate for steady-state errors. The movement to proportional control revealed the difficulties caused by nonlinear components and the initial response was to try to modify all the components in the control chain to remove or reduce nonlinearities including friction, dead space, and hysteresis effects. This approach was similar to that adopted by engineers attempting to develop stable oscillators for transmitting and receiving equipment and by engineers developing repeater amplifiers for the telephone network.

Gradually they realized that the effects of nonlinearities could be diminished by the use of negative feedback. Independent of the work of H.S. Black on the negative feedback amplifier, Clesson Mason realized that by putting feedback around a high gain amplifying device — the flapper-nozzle unit — the overall gain was reduced and a linear stable amplifier could be achieved. There is no formal written report by Mason that expresses the benefits of his invention in the clear terms that Black used; however, he was undoubtedly seeking a means of both producing a linear amplifying device and of modifying its behavior.

In 1922, Nicolas Minorsky presented a very clear analysis of the control actions necessary to provide effective control of a system whose exact dynamics were unknown. He analyzed the actions taken by a good helmsman steering a ship and translated these actions into the appropriate mathematical formulations. He showed that the control action needed to be made up of the sum of three terms related to the error, integral of error, and derivative of error. Minorsky's work was on the steering of ships and was published in the *Journal of Naval Architects* ([32]; see also [33]). How did such work relate to the design of automatic temperature controllers? There was, in 1922, no common language of control systems; engineers did not draw block diagrams showing feedback.

The first drawing together of important ideas from several sources came in 1934 with Harold Hazen's paper on servomechanisms. In this paper, he drew on literature from many disciplines and included an examination of the control actions used in industrial instruments [34]. By this time, however, many engineers working in the instrument companies and in the process industries had discovered for themselves the benefits that feedback could bring. They also were trying to build up a body of theoretical knowledge that would help with future design problems. John J. Grebe and his colleagues at the Dow Chemical Company in the United States and A. Ivanoff in the U.K. led the way with papers published in 1933 and 1934 [35], [36]. The major work, however, began in 1936 with the push, led by Ed S. Smith, to form an Industrial Instruments and Regulators Committee of ASME (see [37]; also [38]). Prior to this initiative, most information relating to industrial instruments and their use appeared in the journal *Instruments*, which began publication in 1928 and whose editor, Major E. Behar was an enthusiastic and tireless proponent of the use of automatic control. Full recognition of the importance of instruments in science and industry came in 1942 when the American Association for the Advancement of Science chose the subject of instrumentation for one of its Gibson Island conferences. Attendence at these conferences was by invitation only, and no proceedings were published — everything was supposedly said "off the record."[12]

Rapid Growth of Industrial Instruments in U.S.

I have discussed elsewhere my views about the reasons for the rapid growth in the use of industrial instruments in the United States and why similar growth did not occur in Europe [40]. In brief, managers of American industry wanted instruments and controllers and were so

[8]The simulator is in the National Museum of American History, Smithsonian Institution, Washington, D.C., and a photograph of the simulator is in [5].

[9]I think a close and detailed examination of the work of the 1920s will show that Ivanoff was only partially correct and that there was some sound theory underlying many control devices. What was lacking was a common language with which to communicate this theory; Chris C. Bissell of the Open University, U.K., argues convincingly about the significance of the development of a language for the expression of feedback concepts and ideas, and I look forward to publication of his work in this area. As Kevin M. Passino argues, it is important to use both intelligent and conventional control as appropriate [28].

[10]In [30] there is a reference to a paper written by Leeds in 1909 that outlined a solution to the problem of hunting in control systems. Unfortunately, I have not been able to find a copy of the paper and hence cannot ascertain if Leeds was advocating such views as early as 1909.

[11]For a detailed account of Sperry's work see [31].

[12]Behar was aware of the significance of the choice of instrumentation for a Gibson Island conference and he published a photograph of the participants (taken by J.G. Ziegler) together with a list of names. See [39].

convinced of their value that they were willing to accept their limitations and to buy new models as the instrument manufacturers learned how to overcome the problems. The early developments were the fruits of the engineer-inventor and it is interesting to note the important role played by one family — the Bristols. William H. together with his father and one of his brothers, Franklin B., formed the Bristol Manufacturing Company in 1889. The company was renamed the Bristol Company in 1892. In the late 1890s, two younger brothers, Benet B. and Edgar H., joined the company. In 1906, the William H. Bristol Electric Pyrometer Company was formed to manufacture and market the base metal thermocouple which William Bristol invented. A disagreement over policy led Edgar and Benet to leave in 1908 to form their own company, the Industrial Instrument Company. This company used the name Foxboro as a trade mark from 1912 and, in 1914, changed its name to the Foxboro Company.

The Leeds & Northrup Company and the Brown Instrument Company were initially dependent on the inventive capacity of their founders, Morris E. Leeds and Edwin Brown, as were many of the 600 instrument manufacturing companies in operation in the mid-1930s. Gradually, the nature of the major companies changed as they adopted a more systematic approach to research and development; for example, the Leeds & Northrup Company formed an Experimental Committee in 1911, the Taylor Instrument Companies operated a research department from the early 1920s, and the Brown Company engaged in routine analysis of its competitors' products and carried out systematic research on improvement of its own products throughout the 1920s. The Foxboro Company was, perhaps, the last of the major companies to form a separate research department. It relied on Edgar Bristol and Clesson E. Mason until the latter part of the 1930s.

In comparison with the large research laboratory of the General Electric Company and the Bell Laboratories of AT&T, the research departments of the instrument manufacturing companies were small. However, simple comparisons of size can be misleading. The instrument companies were research led and spent a large proportion of their turnover on research and development. Their organization was such that sales and support engineers in the field played an important research and development role. The companies were selling not just instruments, but solutions to problems. Field engineers worked closely with customers and became aware of, and expert in, a wide range of measurement and control problems. They communicated information about problems, often with suggestions for solutions or details of improvisations they had made, to the head office of the company. They also carried out field trials of ideas produced by engineers working in the research departments. The effectiveness of this approach is clearly demonstrated by the speed with which the pneumatic PID controller was developed. In the majority of the companies the development of controllers took second place to the development of new measuring instruments until the 1930s. Once they turned their full attention to controllers, the development was rapid. Within a period of five years the major companies were offering PI control and, within ten years, field adjustable PID controllers.

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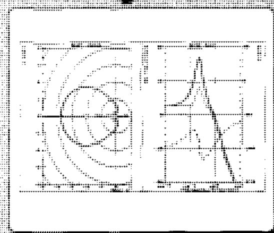

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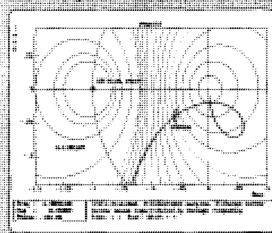

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