CONTROL ENGINEERING AT THE UNIVERSITY OF MANCHESTER IN THE POST WAR YEARS

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Abstract: The purpose of this paper is to outline the leading role the Electrical Engineering Department at Manchester played in the early development of control engineering teaching and research in the UK after the war. The holding of a major UK conference in Control Engineering in Manchester roughly 60 years after the start of this work seems an appropriate time to remind today's researchers of these early contributions and the changes in technology and the university environment.

Keywords: History, education, research, analogue simulation, nonlinear control.

1. INTRODUCTION

The purpose of this presentation is to document the activities in control engineering in the Electrical Engineering Department at the University of Manchester in the two post war decades, that is from 1945-1965. This is important in an historical sense as it was one of the few academic departments in which control research was being undertaken from the beginning of the period and was the first UK department to offer an undergraduate module in control engineering. There have been huge developments in both the theory and practice of the subject since then driven by technological developments. These have produced major changes in hardware and computation facilities both for off line analysis and real time operation. It is hoped that this account of those years, covering both teaching and research, will show some of the early achievements made in control engineering at Manchester University and the technologies of the time used in education.

First, however, some further background might be appropriate for which reference (Broadbent, 1998), an excellent book documenting the early history of the university and electrical engineering at the university until 1998, has been very helpful. It has also enabled certain aspects from the two decades considered to be validated. The university grew out of Owens College which was established in 1851 and received its charter as the Victoria University of Manchester in 1903. It struggled for several years but its reputation and progress improved after 1868 when Osborne Reynolds was appointed as the Professor of Engineering. Mathematics and Natural Philosophy (Physics) had already been established and in 1873 Arthur Schuster, a former student, returned to Physics, after obtaining a PhD under Kirchoff in Heidelberg. A Chair in Applied Mathematics was founded in 1881 to which Schuster was appointed and he moved to the Chair in Physics in 1887. Not surprisingly under Schuster the number of electrical topics taught in Physics grew and this continued under Rutherford, who was appointed to the Chair in 1907, after Schuster's retirement. It was from the Electro-technology group in Physics that the department of Electro-technics was created in 1913, although it was placed in engineering. The strong relationship, however, with Physics existed for many years and until the early 60's Physics students could take an electrical option which involved taking courses in the department. Robert Beattie was appointed from Physics, where he had been since 1896, to the chair with the title Edwards Stocks Massey Professor and Director of the Electro-technical Laboratories with support from a Junior Demonstrator Harold Gerrard. The department grew to four people by around 1930, with an average of around 10 graduates per annum. The 1932 graduation class included for the first time a lady, in fact two of them, and F(Fred). C. Williams, (FC), who did a Ph.D at Oxford on circuit and valve noise under Moulin and returned to Manchester after completing in 1936. From 1936-39 he was responsible for most of the research done in the department and during that period published 20 papers, a prolific number for that time. In 1939 he was awarded his D.Sc but left the university at Easter that year to work in a government research laboratory. During the war years under the leadership of Professor Willis Jackson numbers increased slightly and in 1946 he recruited two new people including, John C. West (JC), a 1942 graduate.

FC had a distinguished war time career being awarded the OBE in 1946 and returned to the university as Edward Stocks Massey Professor and Director of the Electro-technical Laboratories in 1947 after the departure of Willis Jackson. Although he soon changed the department name to Electrical Engineering he retained the Chair title until his death in 1977. Under FC's direction the department grew rapidly and although it became world famous for the demonstration of the world's first stored programme computer by himself and Tom Kilburn in 1948, he encouraged the work of other groups.

2. THE EE DEPARTMENT AND CONTROL

When FC arrived in 1947 he had under him 6 lecturers, including Gerrard, and Higham who had been appointed in 1920. Apart from his own research, at that time on computers, he encouraged research in other areas so that by around 1950, groups covered other areas of electronics, servomechanisms, high voltage engineering and machines. The latter was lead by Eric Laithwaite, who had done his M.Sc under Tom Kilburn, and changed to machines because of an interest in linear motors. FC later worked with this group which did novel work on both rotary and linear induction machines. Control engineering work in electrical engineering departments both in the UK and USA often appeared under the name 'servomechanisms' after its war time usage with respect to fire control problems. Early books which used the word servomechanism in the title were MacColl (1945), James, Nichols and Phillips (1947), Lauer, Lesnick and Matson (1947), Brown and Campbell (1948), Porter (1950) and Chestnut and Mayer (1951). The first to use control in the title appear to have been Ahrendt and Taplin (1951) and MacMillan (1951).

FC was very much aware of control related activities from his wartime radar work; his pre-war work with Blackett on differential analyzers; his work on operational amplifiers and analogue simulation (Williams and Ritson, 1947); and his well known paper on the 'velodyne'. JC after graduating from a three year course without summer breaks, entered the Royal Navy in April 1943 for training in Anti-Submarine Warfare. He achieved the rank of Lieutenant on active service in the Western Approaches. The nature of the work, which is still confidential, involved an interest in feedback systems and automatic control with and without a human operator link. It was therefore not surprising that research and teaching in control were undertaken and when the curriculum was revised around 1950 a final year course on servomechanisms, the first in the UK, was offered to students in both electrical engineering and physics. Lectures were given by JC apart from some initially by FC. The course was popular and lead to the book Textbook of Servomechanisms (West, 1953) which sold over 12,000 copies and formed a basis for much of the teaching of the subject in UK universities and colleges in the next decade, and was adopted by the IEE for its examination syllabus. Laboratory work was an important part of both teaching and research in FC's department and his title including 'Director of Laboratories' was certainly not just nominal. For the servomechanisms course the laboratory included both position and speed control systems and analogue simulations using operational amplifier circuits. There is a distinction between an electronic (or analogue) simulator and an analogue computer in that the former would not just consist of sumers and integrators but typically allowed for other transfer functions to be obtained with an operational amplifier. Also the integrators in a simulator often ran in a continuous mode since providing switching circuits, which at that time were mechanical relays, was expensive.

The initial research work undertaken by JC mainly involved hardware and two papers published in the IEE are given in references (Williams and West, 1951; West, 1952). Reference (Williams and West, 1951) was possibly the first paper on a subject which has had a long control history, namely the positioning of a device to write and/or read from a digital storage medium. Fig. 1 shows a photograph of the magnetic drum. The other paper (West 1952) dealt with a control method for the horizontal motion of large naval guns which had very large inertia. To eliminate steady state errors due to variable load torques, created for example by the wind load, an integrator was required in the controller. For driving to different positions as fast as possible it was necessary to do so with maximum torque, which was the 'course' mode. It was realised that keeping the integrator in circuit during these motions would cause major control difficulties due to integral wind-up. Thus the integrator was only switched in for 'fine' operation when the error was relatively small. This was perhaps the first work to recognise that since integral control is only required to eliminate steady state errors there is no need for the integrator to be kept in continuous operation. Such strategies are much easier to perform with modern technology and it is surprising it does not obtain more publicity. It is, of course, a general approach to avoiding integral wind-up and was studied in a thesis (Rundqwist 1991) and considered in the paper (Bohn and Atherton 1995).

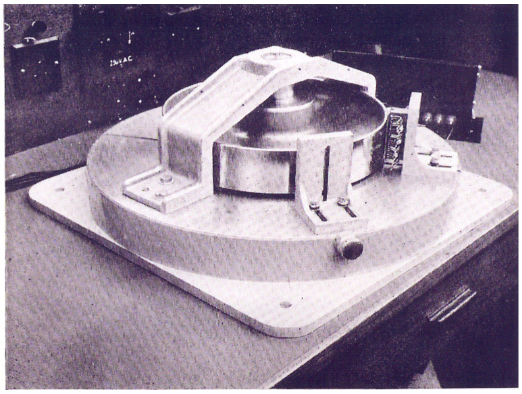

Fig 1. Magnetic storage drum

He also cooperated with Eric Laithwaite on the early work on linear motors which envisaged as an application driving a shuttle in the textile industry, which was a major local industry at the time. The control group grew quite rapidly in the early 50's and by the time JC left to take up a Chair at Queen's University, Belfast in January 1957 around 6 PhD's had been awarded or were being completed.

Of these graduates most had distinguished careers, Jack Leonard was chairman of Eurotherm for several years and Mike Somerville (MJS) became the companies Research Director. Gordon Roberts worked for several industrial companies before finishing his career with Eurotherm. John Douce followed JC to Belfast and later moved to a Chair at Warwick. Peter Nikiforuk returned to Canada and was for many years the Dean of Engineering at the University of Saskatchewan in Saskatoon. Incidentally a previous Dean there, Arthur Porter, wrote the book mentioned earlier on servomechanisms and was a contempary of FC at Manchester. In addition about the same number of students completed Masters Degrees.

The research projects undertaken were roughly half hardware, and half theoretical supported by simulation studies. Some of this work is described in more detail in the next section.

3. RESEARCH IN THE WEST YEARS

Much of the early theoretical and simulation work was concerned with the effects of various nonlinear elements on the step response of servomechanisms, or as usually used in the published paper titles, R.P.C. (Remote position control) systems. The theoretical work made use of the phase plane which allows step responses to be constructed for second order systems with one or more nonlinear elements. These were important considerations at the time and still are today, because with economical hardware design motors invariably run with torque saturation at some time in the response. With integral control present (West and Somerville, 1956) this may cause serious problems in some control systems, as was documented in the report of the Saab Grippen fighter crash in 1989. Later work led to the use of the describing function for predicting the frequency response of these systems with all results checked by simulation. The frequency response work explained how the jump phenomenon could be predicted and showed the different behaviour produced by hard and soft spring nonlinearities.

A very important research contribution was that of reference (West et al, 1956) on the dual input describing function (DIDF). Although the same phrase was used in the American literature around the same time, the problem studied at Manchester was different and much more difficult in that the situation of passing two sinusoids of related, not unrelated, frequencies through a nonlinearity was considered. It is easy to check analytically for a cubic nonlinearity that if a fundamental and third harmonic with a phase difference relative to the fundamental are applied, because of 'beating' between the first and third harmonic producing an additional fundamental component, the fundamental undergoes a phase shift. By discretising the waveforms the work gave graphical results for a saturation nonlinearity. This work took many hours of computing and was only possible because access was available to one of the worlds most powerful computers at that time. This work enabled many interesting aspects, where related harmonics exist, to be studied. These included further aspects of the jump phenomenon, subharmonic generation, and the balancing of two harmonics, rather than the one of the describing function method, to be undertaken for limit cycle studies.

Another nonlinear problem of importance, more so than today because of improved machining, was backlash in gears. For small instrument servomechanisms anti-backlash gears could be used but for large installations it could be a problem. For example, it had a big effect on the design of the Jodrell Bank telescope as it was decided that to achieve the desired pointing accuracy there should be separate drives for the two directions of motion. Dietiker did experimental work on backlash which revealed some very interesting aspects to a problem that is not completely solved today. The simple model available in Simulink, the so called friction controlled model, of two parallel straight lines assumes the friction on the load shaft keeps it in contact with the drive shaft when decelerating and on reversal the drive shaft picks the load shaft up without any change in velocity. The fact that the dynamics are different, when the two shafts are both moving compared to when the drive shaft alone is moving, is neglected. Further on picking up the load shaft on reversal the effect of the impact is neglected and, of course, if this is hard enough it will cause the load shaft to move back across the backlash and repeated impacts can occur. Also any simulation strategies which are used to try and improve performance with this simple backlash model are likely to undermine the assumptions on which it is based. In model based simulation languages, such as 20-SIM better models using springs for the impact modelling are available, but to get the modelling correct for a specific case is not easy.

JC continued his control research in Belfast with Douce and others but also spent some considerable time writing a second control book (West, 1960), this time on nonlinear control systems, which was almost entirely based on his work in Manchester and was one of the first, if not the first, book to be written on the subject. After Belfast J.C. became the founder Dean of Applied Sciences at Sussex and finished his career as Vice Chancellor at Bradford.

4. TEACHING AND THE LABORATORIES

Mike Somerville (MJS) was appointed as a lecturer in 1954 to work in the control group under JC and one of his main tasks was to build up the simulation facilities to support the control theory research. Most of the details of the circuits he designed and that were used in the simulator can be found in reference (Haley and Scott, 1960) and some information has been given more recently in reference (Atherton, 2004).

Perhaps just a few words are therefore appropriate here. The machine used valves and the required voltages were 6.3V a.c. for the heaters and ± 300V d.c. Operational amplifiers with facilities for plugging in input and output feedback components; potentiometers to vary the gain; and various simple units using diodes for nonlinear characteristics, such as saturation; were provided. An electronic simulator being a parallel machine had the big advantage that signals at all points could be observed simultaneously with an oscilloscope, as is now possible today with the high speed achievable in digital simulations. Two big disadvantages were the need to 'patch up' the problem to be solved (if one of the amplifiers went wrong and had its output at -300V touching a bare wire connection would give a nice burn!) and that if the differential equation were nth order then n operational amplifiers, usable as integrators, were required. Further such a facility was not cheap to build; the cost of the components for one operational amplifier was comparable with a week's salary for an assistant lecturer. Another difficulty was recording results although one was helped in this by the fact that the time scale for running a problem could be adjusted to suit the 'sources' and 'sinks' to use modern simulation language terminology. To run a problem on a slow time scale required larger and more expensive integrator capacitors. Thus step response results were often observed on an oscilloscope using a periodic square wave input with the x-y facility providing an excellent way to look at phase plane plots. A Gaussian random signal generator was also available for the research investigating servomechanism behaviour with random inputs.

After JC's departure other facilities were added to the machine, these included phase measuring facilities using a thermocouple wattmeter and sample and hold units to enable study of sampled data systems, which became a popular research topic after the publication of references (Ragazzini and Franklin, 1958) and (Jury, 1958). Improved facilities were provided in the laboratory for the servomechanisms course primarily in terms of simulation experiments. These included a third order system simulator to look at the step response as the gain varied, a second order system with saturation to study various effects including jump resonance, and an on-off temperature control. The description of the experiments sounds perhaps trivial today but there were many challenges which MJS overcame and never reported on in the open literature. One that comes to mind was how do you have students obtain good step response recordings when you cannot run at low speed because simulation is more expensive and plotting tables very expensive. One unsatisfactory answer is to sketch the traces from an oscilloscope screen but the solution MJS came up with was to use a periodic square wave input and a sample and hold sampling at the square wave frequency but with the delay from the input step level variable by known amounts. A d.c. meter them measured the sample and hold output, so students could get a point plot of the response. This was the basis of the much later produced sampling oscilloscope.

The teaching of the group included some measurements to first year, a second year course which included some d.c machines and power amplifier drives and, of course, the final year servomechanisms. It is interesting to reflect on the content of the last two courses since the material taught in the former, being based on the existing technology, is now almost only of historical interest whereas the theory of the servomechanisms course is still relevant today. The former course covered Ward Leonard system drives, d.c. machines with interpole and compensator windings, amplidynes, metadynes, magnetic amplifiers and mercury arc rectifiers. The servomechanisms course still included much material from reference (West, 1953), but added material included simple nonlinear systems with analysis using the phase plane and describing function methods, the SERME system, response to stationary random inputs including consideration of nonlinearity, and sampled data systems. The fact that a student taking just one control engineering course today will probably not cover much of this additional material, delivered in a course around 1960, should possibly be of concern.

5. LATER RESEARCH

After JC left Manchester the research group was lead by MJS and although he continued to support control research he devoted a lot of time, as mentioned in the previous section, to improving the undergraduate laboratory and simulation facilities. The latter were very important to checking out the theoretical results and often required innovative techniques. JC and Nikiforuk had started investigations into nonlinear systems with joint random and sinusoidal inputs and represented the transmission through the nonlinearity by a single gain. MJS felt this could be done more accurately by two gains one for the sinusoid and one for the random signal obtained by minimisation of the difference between the nonlinearity output and that of the two nonlinear gains. This lead to the publication of reference (Somerville and Atherton, 1958) which also proved two other interesting respects envisaged by MJS namely showing that the gains could be calculated by a modified nonlinearity concept and that the gain to a small d.c signal was the same as that to the Gaussian random noise.

These ideas were further expanded on in references (Atherton, 1962a, b; Atherton and Turnbull, 1964). In particular in (Atherton, 1962a) and (Atherton, 1962b) it was shown how other output terms from a nonlinearity, not just the equivalent gain terms, could be calculated, and in (Atherton and Turnbull, 1964), as its title suggests, the paper considers how the performance of a nonlinear system could be altered by the injection of other signals. Relay elements were a major consideration in this paper as they were still an economic practical device for use as a control system power amplifier. This lead to the further work on limit cycles in relay systems, which is described in (Turnbull et al., 1965). To a large extent these research studies were a logical extension of the pioneering interest of JC in nonlinear control problems.

A new area of research which was undertaken was in sampled data systems, which perhaps regrettably, was hardly reported on in the open literature although is mentioned in several theses. To support the theoretical work, as mentioned above, some novel switching circuits were built for sample and hold circuit use and a D(z) block was also built. Simulations as well as theoretical work were done on dead beat responses and systems with random inputs.

The overlap with the JC period essentially finished in 1962, when MJS moved to Eurotherm and the author to Canada.

The group was then lead by George F. Turnbull who expanded the scope of the research, in line with external developments, to include measurements and systems engineering (Broadbent, 1998).

The main focus of the control research was under the heading of "Self-oscillating Feedback Systems" which embraced and continued the work on multiple inputs into non-Linearities (Atherton and Turnbull 1964: Turnbull et al., 1965), but was also concerned with practical applications, and sampled-data systems (Somerville and Turnbull 1962). The sampled data simulator was replaced by a transistorised unit which was superior in all respects – size, reliability, performance etc.

The first type of self oscillating systems to be investigated were amplitude modulation systems and after some initial theoretical work and simulation, a practical system was implemented - a hot-wire anemometer - which was used for the measurement of steady state and turbulent flow in a wind tunnel in the mechanical engineering department (Somerville and Turnbull 1962): this clearly showed the benefits of this approach. As with the sampled-data simulator, the early valve model was later replaced with a transistorised unit.

Virtually in parallel with this work, the second type of self oscillating systems to be investigated were relay feedback systems. Again in line with the general approach, enhancement of the earlier theoretical work was supplemented by a transistorised simulator (Wade, 1966) and a practical example was investigated.

This was a high efficiency audio amplifier (Turnbull and Townsend 1965) which created much interest and debate (Turnbull and Townsend 1967)

In the measurement area the main focus was on non-contact measurement and again an approach of theoretical studies, combined with simulation and followed by a practical example, was adopted. The practical example was a non-contact voltmeter (Turnbull and Jones 1966).

In the systems area work was initiated into multi-variable process control systems.

To back up the wider scope in research work, the undergraduate laboratories and courses were completely overhauled. An example of the approaches adopted was presented at an IEE conference (Turnbull and Jones 1966)

G.F Turnbull left in 1966 to join M.J.S. in Eurotherm. He was followed by J.M. Townsend and P.A. Wade and this lead to a very efficient technology transfer of the research work in the period 1960 – 65 into a highly successful range of control equipment. Other researchers like Lutte N.P. (Broadbent, 1998) followed later and in fact Professor Williams often jokingly referred to Eurotherm as his 'Southern Department' and inside Eurotherm these people were described as the 'Manchester Mafia'. Eurotherm was highly successful and was finally sold in 1998 for £400M to the Invensys group.

6. CONCLUSION

The Electrical Engineering Department at Manchester was an extremely highly regarded institution in the post war years under the leadership of, later Professor Sir F C Williams. The computing work is well documented but less so some of the other achievements, such as measurement and control. With respect to the latter it was one of the few universities to be undertaking control research at that time and the first university in the UK to introduce an undergraduate course in control engineering under the title 'servomechanisms'. These developments took place under, John West with the strong support of FC, and resulted amongst other things in two original textbooks. Professor West had a distinguished career moving from Belfast to be the first Dean of Applied Sciences at Sussex and then to be Vice Chancellor at Bradford. He was awarded the CBE and also served as a President of the IEE. This paper has tried to give a brief overview of the work undertaken which provided a major basis for the development of one UK company, much subsequent industrial and academic research and two further books (Douce, 1963, Atherton, 1975).

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