15th Triennial World Congress, Barcelona, Spain

THE ROLE OF ANALOGUE COMPUTERS IN CLASSICAL CONTROL DESIGN

Derek P. Atherton

University of Sussex, School of Eng. and Information Technology,
Falmer, Brighton BN1 9QT UK. d.p.atherton@sussex.ac.uk

Abstract: This paper looks at analogue computers and their role in the development of control engineering. Vacuum tube analogue computers were used extensively from the mid 40’s to the mid 60’s and the paper describes their general features and those of some specific machines. Later work involving machines with transistors and then integrated circuits is briefly discussed. Some discussion is included of how the machines were used both in education and industry to further the discipline of control engineering. Copyright © 2002 IFAC

Keywords; History, analogue computer, education, operational amplifier, electronics.

1. INTRODUCTION

Control engineering started to emerge as a discipline in the late 30’s and early 40’s and simulations at this time were initially done using mechanical devices, such as the ball and disk integrator incorporated into differential analysers. The following two decades saw a rapid growth in control theory, often referred to as classical control theory, but perhaps more precisely described as that control theory which existed prior to the formulation of state space methods, and a rapid advance in electronics particularly vacuum tube amplifiers. This led to the development of electronic analogue computers for simulation. Their capabilities, accuracy and components changed with time as electronics developed from the use of vacuum tube circuits, to transistors and finally integrated circuits. They were employed both for teaching and research in universities with some institutions building their own equipment. This, in fact, became quite a popular activity in the 60’s and early 70’s where researchers increased their capabilities by interfacing to the newly developed small digital computers, such as the PDP8, to provide so-called hybrid computers. Several companies manufactured analogue computers which were sold to both industries and universities. The manufacture of analogue and later hybrid computers was essentially the sole business of some companies, such as Electronic Associates and Applied Dynamics, but for other companies such as Solartron and Telefunken analogue computers were just one of a diversified range of products.

Analogue computers used to support the teaching of control engineering were mainly initially, but not entirely, confined to electrical engineering departments where there was less reluctance to connect things together with wires, but as commercial products improved they became more common in mechanical and chemical engineering departments. They were used to illustrate many basic concepts of linear control theory and in some cases to introduce students to the effect of commonly occurring nonlinearities, such as dead zone, saturation and backlash.

In industry and government laboratories analogue computers were usually used to simulate larger systems than in academia, usually incorporating more realistic models. The latter invariably meant the inclusion of nonlinear elements for which theoretical analysis and design approaches were lacking. It was therefore common practice to do any theoretical studies on a linearised system and then study the full nonlinear system with proposed controller designs on the analogue computer. Analogue computers were also used in industry as components of training simulators, perhaps the best known being flight simulators, but this usage will not be considered further in this paper.

The paper is organised as follows. The next section discusses the basic components of analogue computers, their development and computer operation. Section 3 describes some specific analogue computers and includes some personal recollections of the analogue computer installation at the University of Manchester. The objective of section 4 is to illustrate uses of the analogue computer in studying control engineering. The major emphasis will be placed on its use in teaching and research in academia, where my own experience was obtained.

2. FEATURES OF ANALOGUE COMPUTERS

Simulation using analogue techniques developed quite significantly during the war time period in government laboratories in the U.K. and U.S.A. The major need for simulators was for studying the design of military equipment for fire control, tracking and missile guidance. Linear analysis allowed some estimation of control system behaviour but simulators were required to look at more complex models than used in the basic analysis and particularly the effects of nonlinearity. The technology and manufacturing of products in those days was such that nonlinearity was far more prevalent than might be the case today. Backlash in gears, nonlinearity in amplifiers and motors, nonlinear friction and the need deliberately to use nonlinear components, such as relays, because economically they were a good form of robust power amplifier. Unlike integrated circuits used today, vacuum tubes did not take 'kindly' to operation in harsh environments, for example of high temperature and vibration. An excellent paper describing analogue computers of that era is by Williams and Ritson entitled 'Electronics Servo Simulators [Williams F.C and Ritson F.J.U. 1947] and one describing usage in a practical investigation is [Ritson F.J.U.and Hammond P.H. 1952].

The heart of the analogue computer is the d.c. amplifier. Simulation of a linear second order differential equation is normally done in terms of the controllable canonical form block diagram requiring two integrators a summer and some variable coefficients. To set initial conditions on the integrators and to pause the simulation requires suitable switches. This was not easy to do efficiently with 1940's technology so many early vacuum tube analogue computers were either off or running continuously. When this approach was used the amplifiers were often provided with external sockets so that different impedances could be attached for the input, often more than one, and feedback components. Another factor that dictated this approach was the relatively high cost of the amplifier compared to components, such as resistors and capacitors. An analogue circuit designer, for instance, wishing to produce a second order filter would do so using resistances and capacitors around a single amplifier. Research was done in the 50's on how one could produce higher order transfer functions using a single amplifier – quite a different philosophy to today when the amplifiers are cheap.

The vacuum tube circuits required 6.3 V a.c. for the heaters and d.c. amplifiers were typically supplied in addition with a voltage in the range ±150 to ±300V. The linear output voltage range was normally around ±100V. A difficulty in d.c. amplifiers was to avoid d.c. drift, that is the output drifting from zero when the input is zero. The input stages of the amplifier circuits were long tail pair circuits and the positive terminal was not available as an input as it was supplied from a variable d.c. voltage to provide zero setting, that is adjusting the output to zero with zero input. High gain amplifiers were required to ensure that transfer functions were accurately defined by the input and feedback impedances so sometimes zero setting was done with the amplifier gain reduced by feedback to the order of 100. Special chopper stabilised d.c. amplifiers were built to overcome the drift problem but they were relatively very expensive and with the continuously running simulator were really only necessary if integrators were to be connected in open loop.

Fixed gains, when required, were produced by using different input and feedback resistors, typically available in steps of 10, say 10kΩ, 100kΩ and 1MΩ. To produce accurate gains these had to be high stability, low tolerance components. Variable gains were obtained using potentiometers of around 10kΩ, typically ten turn, to allow for fine adjustment. To avoid loading problems due to amplifier input and output impedances potentiometers had to be set ' 'in situ' ' High quality low loss capacitors were needed and values above 0.01μF, as they were required also to withstand high variable polarity voltages, were extremely expensive. Electronic signal generators were used to provide system inputs and oscilloscopes, sometimes with recording cameras were usually used for monitoring the voltages at various parts of the simulation. Biased diode circuits were used to provide nonlinear characteristics. Some machines had so called variable function generators where gains (slopes) and breakpoints of functions were adjustable with the d.c. voltages applied to the diodes. Whilst commonly used circuits, such as ideal saturation and dead zone, were often built in.

The major problems with early machines were in the setting up procedures which had to take account of reliability and the requirement for time and amplitude scaling. Plugging in components and connections between units did not 'go down well' with non-electrical engineers. Reliability of components made modular programming a necessity, long before the digital computer people coined the phrase. One always checked each part of a simulation in sequence due to the possibility of amplifier or component failure, broken wires etc.

Time and amplitude scaling came into prominence more when simulation was used for a specific system. For academic like studies, say for example the investigation of jump phenomena in the frequency response of a second order system, no amplitude scaling need be done and the time scale could be chosen to suit the measuring equipment. With a specific physical system simulation both amplitude and time scaling would normally be required. Time scaling to run the system at a suitable speed for the studies envisaged and amplitude scaling in terms of how the voltage at a particular point was related to the physical variable it represented. Although 'a chore' this was good engineering practice as one knew that if the output of a particular amplifier represented a current one should not, although it would be possible, as perhaps regrettably so in today's digital simulators, connect it to an input which represented temperature.

The major change when transistor based analogue computers became available was that the circuits typically operated on ±15Vd.c., so that the linear range for the operational amplifiers was ±10V. Also because of improved transistor circuit design, both of amplifiers and switches, it became much easier to provide controlled integrators with time constants of one second or longer, All commercial computers had the three modes of initial condition, run and hold so that the solution could be frozen either at any time or possibly on the occurrence of a specific event. More numerous nonlinear features started to appear and with the advent of integrated circuits the cost of amplifiers and multipliers became relatively cheap. This meant that the volume occupied by the electronics became quite small relative to that required for terminals and patching, in contrast to the situation in vacuum tube machines. So called hybrid computers, started to appear in the 60's, with parallel digital logic and sometimes interfaced to a small digital machine. Other functions, such as track-store, were implemented in analogue form as were data sampling and A/D conversion. The interface to a digital machine allowed for easy simulation of time delays and for digital processing of signals to evaluate correlation functions and spectra.

3. SOME REFLECTIONS ON SPECIFIC MACHINES

The purpose of this section is to describe some features of specific analogue computers and to include some personal recollections. The major concentration will be placed on the early years when vacuum tube machines were used. The heart of these machines as mentioned earlier was the vacuum tube d.c. amplifier. An excellent book on the status of this technology in the late 40's is Vacuum Tube Amplifiers published in the Radiation laboratory series by McGraw Hill, a series better known to control engineers for the book Theory of Servomechanisms. One of the co-authors of the book on amplifiers was F.C. Williams, who in the war years was a 'boffin' at TRE in Malvern UK. He did a lot of pioneering research in this field and maintained close contact with MIT. After the war he took up the post of Professor and Head of the Electrical Engineering Department at Manchester. He was an outstanding engineer who after studying E.E. at Manchester went to Oxford where his D.Phil was on noise in vacuum tubes. During the war years he made many major contributions to electronics, radar and control and after taking up his position at Manchester was responsible for starting the research there on digital computers. He is perhaps best known for producing one of the first computer storage devices using a cathode ray tube, which became known as the Williams tube in many countries. Research in control engineering developed at Manchester due to his influence and one of the early projects was implementing suitable speed control on magnetic drums also used as a digital storage medium. Incidentally the IEE has for many years awarded a prize, called the F.C. Williams Premium, for an outstanding publication in its Proceedings on Control Theory and Applications. By the mid 50's he had again changed his research field to variable speed a.c. machines and linear motors. He had some interesting research philosophies one of which was essentially if you are no longer ahead of 'the pack' then it is time to change. No doubt his switch to electrical machines stemmed from his recognition of the immanent expansion of digital computer research. Very much a source of ideas and an experimenter he also addressed the problem of shortage of fuel in the post war years. For example, he investigated fly-wheel energy storage for an automobile and once caused a small fire in the laboratory when doing some work on an internal combustion engine. When the firemen arrived he was in the laboratory in his lab coat looking as usual very much the technician and a fireman was heard to remark to him "I am afraid you'll be in trouble when the professor finds out".

I went to the University of Manchester in 1956 after graduating in Electrical Engineering from Sheffield University. The undergraduate lectures I had received on control were minimal, limited to the concept of the simple feedback loop with constant values in the elements to illustrate aspects such as the value of high loop gain and accurate sensing. It was perhaps rather surprising therefore that I opted to go on and do research in control, but I had gained the opinion that there were challenging problems and the discipline used the sort of mathematics that I enjoyed. At the time there were three university Departments in the UK leading research in control, one at Cambridge led by Dr John Coales and one at

Imperial College led by Professor Arnold Tustin, who had recently moved from Birmingham, and was supported by Dr John Westcott, and in Electrical Engineering at Manchester University a group led by Dr John West [Broadbent T.E.,1998]. John West was supported by Dr Mike Somerville and Dr John Douce who held a research appointment. Shortly after I arrived in Manchester John West moved to a chair in Belfast and persuaded John Douce to follow him a few months later. The courses taught by the group of one semester duration were a measurements course in first year, a d.c. machines and power amplifiers course in the second year and a final year control course, which in addition to classical linear control contained a few lectures on nonlinear problems and random signals

Mike was responsible for the first two courses and the analogue computer, which he had designed and was built ‘in house’ by the technicians. He was a gifted practitioner and electronic circuit designer and later became technical director at Eurotherm. It was on the basis of his clever controller designs at the start of the changeover to electronic controls in industry which provided the company with its initial rapid growth.

This analogue computer used vacuum tubes and was primarily used in a continuous mode with the operational amplifiers able to provide single transfer functions, by the appropriate use of feedback and input impedances, as well as summers and integrators. The power supplied from bulky power supplies fixed to the lowest level of the post office racks on which the computer was ‘housed’ supplied ±300V d.c. and 6.3V a.c. for the heaters. The use of ± 300V d.c. meant that it was not unknown for an error or fault to occur in which an amplifier output reached one of these levels and touching the metal rather than the insulation of a connecting wire could produce a nasty little burn on the finger. None of the amplifiers were chopper stabilised to avoid d.c. drift so in general integrators were only run open loop for a short time, for example to integrate the squared value of the error. This meant compromises because although the computer performed best when running fast this was often not compatible with the requirement to get hard copy of signals. For example, suppose one wished to simulate a position control system and look at the effect which different levels of torque saturation had on the step response. The natural frequency of the system might be around a few radians per second but one could simulate it a thousand times faster and apply a square wave input from a signal generator. The time domain response or phase plane waveforms could then be observed on an oscilloscope, which did not need to be a long persistence one. Obviously if one made changes to a parameter its effect could be observed very quickly at this speed. Although cameras were available to take photographs of the oscilloscope screen this was relatively expensive. The available hard copy device was typically an x –y plotter, which would have cost more than half my annual salary as an assistant lecturer in 1958. With a plotter bandwidth of a few hertz the step response could only be plotted with the computer on a very slow time scale. A slow time scale meant large integrator time constants, which in practice were limited by the maximum value of feedback capacitor available, which had to be low loss and handle more than ±100V.

As mentioned above ‘sources’ to use the modern term of SIMULINK were typically signal generators with sine, square and possibly triangular waveform outputs. Noise generators also became available. These were signal generators producing a random signal with a near Gaussian distribution of wide bandwidth. The Manchester computer had a home built one which used a gas filled vacuum tube. One way to measure the phase of a sinusoid is ‘to cancel it out’ with a signal of known sine and cosine components. Another source available was therefore a signal generator which produced two orthogonal sinusoids.

‘Sinks’, to use the SIMULINK term, consisted of oscilloscopes and plotting tables, as previously mentioned. Using these observations of many variables could be made with a slow running simulation. Means for measuring the phase of sinusoids for frequency response evaluations were also available using signal generators and oscilloscopes. Thermocouple wattmeters were introduced around 1960. Mike designed his own for the Manchester machine which was very similar to that marketed by Solartron as a transfer function analyser.

The Manchester machine had only a few nonlinear units. These included diode circuits to produce sharp break point characteristics with a bandwidth of typically 1kHz, for dead zone, saturation and relay characteristics. Two multipliers were provided one based on a pulse width-pulse height modulation technique and the other on the so called quarter squares principle. This employed two square law characteristics synthesised from diode circuitry and used the relationship:-

$$0.25[(x + y)^2 – (x - y)^2] = xy.$$

Patchable circuits were employed to simulate hysteresis and backlash.

Another desirable feature which was difficult to achieve with analogue computer techniques was the simulation of a time delay. Early methods usually involved simulating a Pade approximation. A colleague produced what he said was an excellent approximation for a time delay, a transfer function of around numerator order 8 and denominator order 10. The difficulty then was to obtain a theoretical solution for its accuracy. Another method used was a tape recorder with fixed write and read heads but with a variable speed drive to vary the delay.

Analogue computers, certainly in the early days, were used as simulators for continuous systems An interest in sampled data systems was stimulated at Manchester in the late 50's with the publication of the books by Jury, and Ragazinni and Franklin. Mike therefore took up the challenge to design a suitable sample and hold circuit. The design was not easy as it required a switch which enabled a capacitor to be charged in a very short time with the switch closed and hold its charge when open for the longer hold period. Indeed the work went much farther. By arranging to slightly stagger in time the pulses which closed the switch several units could be connected to provide a low order pulse transfer function D(z). In retrospect, this work was very interesting and if there had been today's pressures would have undoubtedly resulted in several journal publications but sadly there were none.

It is perhaps of value to look at costs associated with various activities relative to today's prices. The relative costs for purchased equipment to salaries was basically higher than today as has already been indicated by reference to an x-y plotter. Relative to the starting salary for a lecturer around 1960 a chopper stabilised operational amplifier would cost a few months salary and even the cheapest with no stabilization at least two weeks. Since good technician support of roughly one technician per teaching staff member was available it was economical to build equipment in-house. The budget for equipment and components must have been comparable with the teaching salary budget. This is different from the situation today in UK universities where the figure is probably around 0.1 to 0.2 and fewer technicians are also available. The performance to cost ratio for equipment has of course increased significantly over the years. But the originators of this technological development have surely 'missed out' in a climate where funding for electronic equipment in universities has declined dramatically. This funding dating back fifty years supported technical developments which now underpins the entertainment and sports industries . Practitioners in these industries now receive huge salaries because the electronic technology enables them to be seen and heard in every living room. More regrettable is the fact that the Electrical Engineering Department at the University of Manchester has closed. The result of a political climate where student numbers count and the pursuit of an ill-advised strategy, which will do significant damage to the UK engineering industry, of unjustifiable targets encouraging 40 – 50% of 18 year olds to attend university.

Simulators were required by the government defence agencies and industry, in particular for studies of high-speed flight of aircraft and guided missiles. Typical of one such installation was TRIDAC, a large analogue computing machine [Spearman FR.J. et al. 1955] installed at the Royal Aircraft Establishment in the UK. (the acronym stands for *tridimensional analogue computer).* The project took four years from its conception in 1950 to completion in 1954. The machine used electronic, mechanical and hydraulic components, and was housed in its own building. The power consumption was 600kW of which 200kW was for the electronic components, including more than 8,000 vacuum tubes. It cost around £0.5 million, which in today's terms would be well over £20 million. The same problems it was designed to study would now be solved with a standard simulation language on a good PC. Some pictures of TRIDAC and other analogue computers will be shown during the presentation.

Papers published in the IEE at that time were often also presented at Savoy Place and the discussion recorded and published with the paper. A contributor to the discussion on TRIDAC was John Coales whose comments were:- ''The paper raises important questions about the relative merits of analogue and digital computers. When I first became involved in the design of this computer, in 1948, I thought that analogue computers were on their way out and digital computers would replace them. I now think quite differently, partly because of the experience of TRIDAC, but partly because of other considerations met in solving nonlinear problems where one great value of the analogue computer is that a very much better appreciation is obtained of how the process being investigated really behaves. With an analogue computer one can see what is going on in different parts of the system while it is actually happening, whereas with the digital computer, although one can make provision for doing this by printing out different results from within the process, one cannot easily see what is happening while the process is being worked out''.

I quote John not because his prediction has proved wrong but because he clearly identified the short comings of digital simulation at that time and the required features that digital simulation would have to achieve with improved technology for it to be acceptable. Clearly a modern simulation language such as SIMULINK has these capabilities.

4. USES IN CONTROL

In universities analogue computers were used for research and teaching. The research computer at Manchester has been discussed in the previous section and it was primarily used for investigating various aspects of nonlinear control. Initially in the early 50's much of the work was concerned with the effects of various nonlinearities in position control systems. Several papers were published using phase plane methods, which were easily checked by simulation, looking into the effects on the step response of error limiting, torque saturation and nonlinear friction. Results were also produced on the time optimal response for the double integrator system, known as SERME, the acronym for sign error root modulus error, the shape of the required nonlinearity to control the torque switching. Work then moved on to the frequency response of these and other nonlinear systems and led to the extension of the describing function to the dual input case. The initial use of the term by West et al [West J.C., 1960] was for the second input either a bias. sine, or a related harmonic. The latter was required to look at such problems as the forced response of systems which might display a related harmonic oscillation, i.e. subharmonic oscillations. To analyse this situation required the determination of the response of a nonlinear element to the simultaneous application of a sinusoid and , say, its third harmonic. The output is then a function of four parameters, not two. These are the input amplitudes, the frequency ratio and the relative phase. Needless to say this analysis used an enormous amount of time on the department digital computer as the program sampled the waveform for a specific choice of the four parameters, passed it through the given nonlinearity, say ideal saturation, and performed Fourier analysis on the output samples. Later work built upon the random describing function approach of Booton to consider problems involving a random signal plus bias or/and an harmonic.

To support the undergraduate control course several experiments involved analogue simulation, typically using simulators designed for a specific investigation. For example a second order position control system in which nonlinear elements could be included and a temperature control system involving an on-off nonlinearity with variable hysteresis. Standard supporting equipment was a signal generator and an oscilloscope. Step responses were usually considered and methods using frequency responses concentrated on the amplitude, for example in a jump resonance investigation, rather than the phase as this was difficult to measure accurately with an oscilloscope.

As mentioned previously analogue simulation work in industry and government laboratories tended to be for the study of relatively large systems. The main uses were in the aerospace and chemical industries, where some companies built their own machines before turning to commercial purchases when transistor machines came on to the market. People whose role was to program and run specific simulation studies were employed as simulation experts. The 'size' of problems was restricted by the number of integrators on the computer and this also affected the number of people involved. For undergraduate work transistor machines with typically around 10 integrators were built commercially.

5. CONCLUSION

The objective of this presentation has been to provide some idea of the early uses of electronic analogue computers in control engineering. The paper has concentrated on the vacuum tube era and has covered usage primarily in universities for research and education but also in industry and government laboratories. It has tried to bring out not only the technical limitations of early simulation techniques but also the cost of doing various simulations. Both these aspects improved with the introduction of transistor and then integrated circuit technology but despite this the analogue technology has eventually 'lost out' to today's digital simulations which essentially provide all the features that the simulation specialist could only dream of 50 years ago.

ACKNOWLEDGEMENTS

The author wishes to acknowledge helpful comments received from Professors Percy Hammond, John West and John Westcott.

REFERENCES

Broadbent T.E., "*Electrical Engineering at Manchester University"*, University of Manchester, ISBN 0953120309, 1998.

Ritson, F.J.U. and Hammond, P.H., "*The Design and Testing of an Electronic Simulator for a Hydraulic Remote Position Control servo Mechanism"*, Proc.I.E.E, Vol.99, Part II, No.72, December 1952

Spearman F.R.J, et al.,*"TRIDAC: A Large Analogue Computing Machine"*, IEE monograph, Paper No. 1899M, October 1955.

Williams F.C. and Ritson F.J.U., *"Electronic Sereo Simulators," JIEE,* 94 (IIA), pp. 112-24, 1947.

West J.C.,*"Analytical Techniques for Nonlinear Control Systems"*, E.U.P. London 1960.