Control Engineering

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Lecture - 04

Harold Black had this strange or even crazy idea of changing the amplifier configuration in the following way. You take the output of the amplifier and through an attenuator get a reduced portion of it and then, put that in series with the input to the amplifier in a particular way, what will happen? What he did was subsequently known as negative feedback and we will see the reason for the use determined negative but keep it in mind that negative feedback may not always turn out to be actually negative, even in the case of an amplifier.

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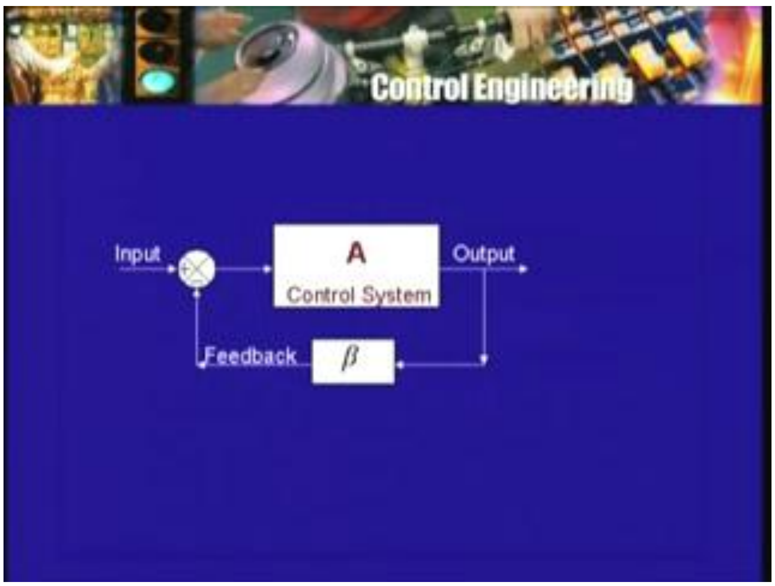

So just putting a minus sign does not give you negative feedback. Well, then with this idea of Black of putting a portion of the output in series with the input, what of course immediately happened was that the gain of the amplifier was changed, in fact the gain of the amplifier was reduced. So, what was the whole point then if by doing this the gain of the amplifier is reduced then your hurting your own cause, you are amplifying and the on the other hand you are reducing the gain with the same amplifier, what happened and it is not immediately clear that this is, what is going to happen is that the amplifier becomes less sensitive to certain variation, in particular the amplifier becomes less sensitive to variations in its own gain without feedback.

Of course what happens is the more insensitive, the amplifier becomes after the introduction of feedback, the less is it is gain going to be and we will write down some equations later on, to see how this happens. I mentioned that in the telephone system, the problem was that when an amplifier went bad one option was to change the amplifier but if that was too expensive we would change some components. For example, a vacuum tube which was the typical trouble maker because on the filament of the vacuum tube by its repeated use or continuous use would run out literally, it would reduce the amount of electron emission from the hot cathode and two tubes of the same type were not identical, their parameter mu which was called the gain parameter of the amplification factor of the vacuum tube would not be the same. The new tube with which we replace the old tube may have a different mu as result the gain of the amplifier would change.

Now, of course one can think of making some adjustments in the gain of the amplifier but then, that requires actual measurement on the spot it is certainly much easier to replace the fuse bulb by another than to start making some measurements and find out what is wrong and what not now. With Black's invention he eventually got a patent for it by introducing this negative feedback in an amplifier, the new gain of the amplifier that is the amplifier gain from the old input with the new configuration to the new output although it is less then, the original gain it is less sensitive to variations in the gain itself, one uses the symbolic capital A for amplification and subsequently the symbol Greek letter, beta was used to represent the fraction of the output that was fed as it was said in series with the input then, if this A beta product was large then, there was a reduction in the sensitivity.

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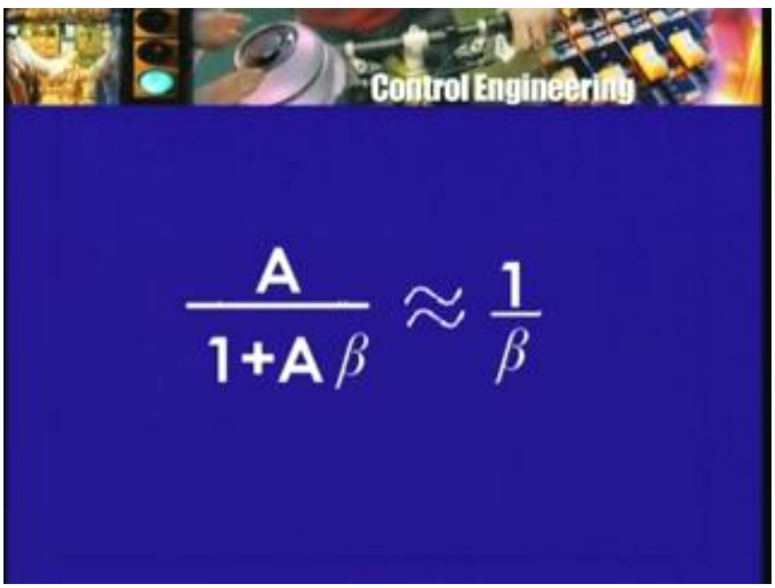

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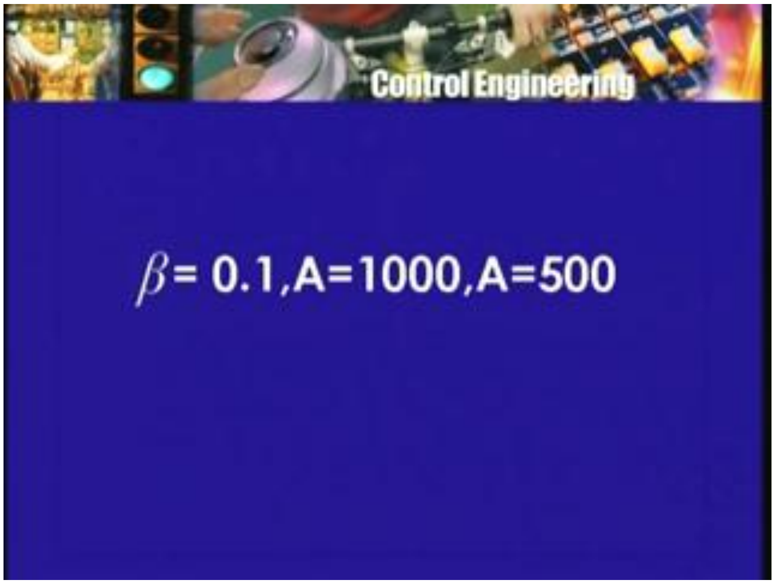

But with the reduction in sensitivity the gain of the amplifier instead of remaining A of course, not only was reduced but it become 1 by beta and you can in fact, the formula for the gain of the amplifier with feedback is A divided by 1plus A beta. So, you can calculate for yourself if A is 1000 and beta is .1, what will be the new gain and if A changes from 1000 to 500, what will be the change in the gain, originally the gain changes from 1000 to 500 by a factor of 2, there is a reduction by a factor of 2 but with feedback with A equal to 1000 beta equal to .1, A equal to 500 beta .1 you will find that the change in the gain is not 50 percent but is less.

So the amplifier as a become less sensitive to what, I have called earlier as parameter variations and what applies to mu can also apply to parameters or aspects of the system like power supply voltage, the battery may be running down slightly and things like that. Now, this was referred to as stabilizing the amplifier, what we meant was you stabilize the gain of the amplifier you made it stable under changes of parameter value, you made less sensitive, a better expression perhaps would have been desensitizing the amplifier because this use of the word stability is different or stabilizing is different from the word, from the use that you will see later on when we will talked about system stability, margin of stability and so on and so forth.

So desensitizing of the amplifier is what was done and of course this is based on a important assumption as said that, if A and beta are appropriately chosen the parameter the gain of the amplifier is stabilized and it becomes very close to the value 1 divided by beta. However, this is based on the assumption that the attenuation factor beta will remain constant.

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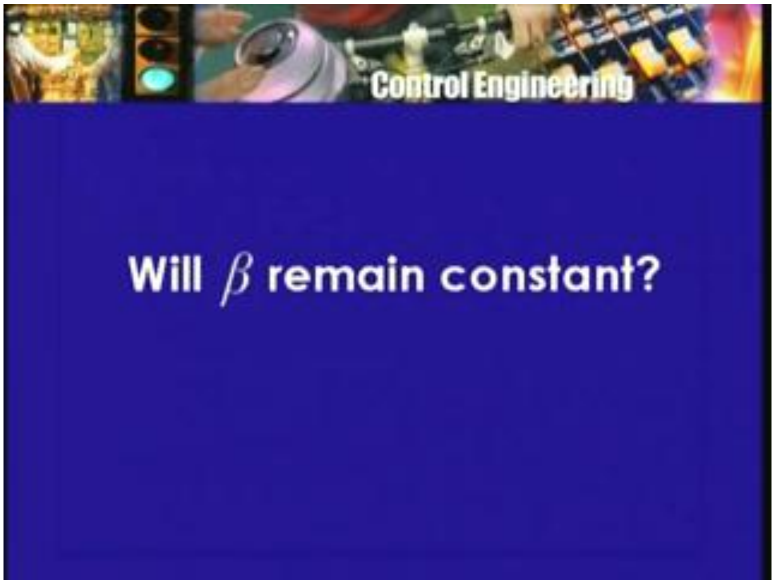

Now, that was the case because an attenuation when can be simply obtained by a potentiometer or by resistance network, simple resistance divider network and this unlike the vacuum tube is not going to change so much. Of course, we saw earlier that resistor values do change with temperature. So they not absolutely immune to environmental effects but the attenuation factor beta is likely to remains stable, likely to remain unchanged and so the overall gain of the amplifier or the amplifier gain with feedback will be nearly constant, independent of changes in the parameter of the amplifier. This was a Black's ideas and of course, he implemented it and he demonstrated it is practical utility.

However, very soon they discovered some problems and I mentioned earlier that feedback can do some things which are good but it can also result in some problems, what happened is, in some situations the amplifier, if you connect it and an of course it was in a telephone system. So if you connect it the output of the amplifier to loudspeaker or to earphone, the amplifier would start singing or the singing output event become a violin and this is an instability.

This is not related to the sensitivity or the lack of sensitivity, higher or lower sensitivity of the amplifier to parameter changes but this is actually oscillations being produced by the amplifier, even when there is no input and this is instability of a certain kind and control theory books have a whole chapter devoted to investigation of stability and instability of a control system, stabilizing a control system, margins of stability and things like that and we will take a look at that later. But soon after, the feedback idea was introduced for amplifiers, this difficulty was discovered and this required that one could not simply produce a things and do something of course that is a good starting point but one has to sit down and do some analysis or study of, what is going on and this was indeed done by people in the Bell telephone laboratories of that time. One of them was Henrik Bode, the last name is sometimes pronounced as Bode but the Americans normally call him Bode.

Henrik Bode studied this phenomenon in detail and subsequently a very big book came out of it which was devoted to the design of feedback amplifiers and in your electronic circuits course dealing with analog circuits. You would have probably already encountered the use of feedback in amplifiers, feedback of various types, series feedback, shunt feedback, voltage feedback, current feedback and what not, Bode's study shed some light on what could happen and therefore, one should do the design in such way that the singing was eliminated and yet, you had an amplifier which was stable, stable with respective parameter changes. Of course, there were limits to what could be done and that is what in fact Bode's work shows and is how for can you go this problem was also looked at by another engineer mathematician at the Bell laboratories, his name was Harry Nyquist and he discovered a way of finding out, when a feedback amplifier will become unstable in the sense it may produce sustained oscillations and indeed there is a test or your criterion for stability known as the Nyquist criterion and once again, we will be looking at it in more detail.

So Black is work led to a solution of the problem of effect of parameter changes but also led to the possibility oscillations and therefore, investigations by Bode Nyquist and others. So in fact when the oscillation produced one will say that the feedback which was intended to be negative has now become positive and as a result in fact, one found out a way of generating oscillations by using feedback and once again, in your electronics circuit course you probably been exposed to some of these oscillators, oscillators with gain produces simply oscillation is not that difficult and inductors and capacitors can products some oscillatory behavior but if you want an oscillator with a gain.

So you have to use a say either vacuum tube or nowadays of course a transistor or you have the transistorized circuit then you can use negative feedback to produce oscillation.
So instead of inductor and capacitor for example you have an oscillator which does not use inductor but uses only capacitor and resistor, what is called it is a called RC phase shift oscillator this oscillator does not use an LC circuit or what is called a tank circuit of the old, the radio receiver era of course such LC circuits are still used but this circuit used only C and R, no L however, it used feedback in an appropriate manner and the feedback could be called positive feedback that resulted in oscillations.

So here was a novel way of producing oscillations having only one of the two reactive elements inductor and capacitor having only one namely capacitor, of course if you can have a RC phase shift oscillator one could think of an oscillator which was one inductor and resistor and that is possible. This singing effect one can produce quite very simply in a laboratory, you can try it even in your own home, if you have an amplifier therefore you would have micro phone as well as a loudspeaker and this effect is some times produced unintentionally or if people people are not careful in an auditorium where, there is a public address system being used that is, there is a microphone into which the speaker speaks, the output of the microphone goes to an amplifier, the output of the amplifier goes to the loudspeakers.
Now it can happen but unless the loudspeakers are properly placed the microphone may phase the loudspeaker. So in other words it will receive sound from the loudspeaker in addition to or even instead of the speaker and as a result the singing can be produced. It can result in a large volume of sound, if you are not careful it could even damage the system on the amplifier of course, there are protective devices such as fuses and so forth but it can be quite damaging to the

ear. It can produce the very shrill sound perhaps some of you can think about what determines the frequency of the sound that is produced then, you have this effect using a microphone and a loudspeaker and an amplifier in between. There was a side effect of this development as I told you, this development started around the late 1920's and the analysis continued in the 30's and 40's amplifiers electronic equipment was becoming very important as the war was approaching and during the war.

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So that is the reason why so much time was spent of course communications even non-military communications were important, so the telephone network was still important to the Bell labs. So the techniques that were used to study feedback and amplifiers were becoming familiar to a lot of people. Now basically an amplifier for a telephone network takes speech signals as a input which somebody is voice or some music which is going to be transmitted across a distance.

Now the speech or music has certain special characteristics will start using word signal, you are already probably familiar and have used that word before. So, one can talk about speech or the music of the corresponding electrical output of the transducer microphone. So in that sense the electrical signal that results from speech or from music this is of a special kind, for example if you play a the single note on a musical instrument then the signal that is produced this almost almost sinusoidal is almost the sine wave of a particular frequency corresponding to or called the pitch of the sound and some instruments or many instruments produce a signal or an output which does not consist of a pure note as it is called or a pure tone but it consist of a number of different frequencies together as you now of they are called the fundamental frequency and its harmonics and of course, when you speak or when you play music you do not only play pure tones in fact no instrument hardly any instrument will produce the pure tone.

So this speak signal of the music signal is more complicated then that but it can be analyzed in terms of in terms of Fourier series. Now of course you where about Fourier series in you mathematics courses earlier. So the method of analysis looks at this signal the say the speak signal or the music of the sound signal in general and tries to analyze it in terms of Fourier series and of course Fourier series is not enough because of a signal is not periodic. As I talk the output that I produce if you watch it on the oscilloscope you will not see that it is periodic, so an extension of it which in fact Fourier himself had suggested for a different reason namely the Fourier integral is used in the analysis.

Now associated with Fourier series on the Fourier integral is this idea of a sinusoidal function and a sinusoidal function has a frequency of course if it manifests physically as light then you would talk about wavelength also or even in the case of sound, one can talk about wavelength but since we are looking at it as an electrical signal one talks about it in terms of its frequency or period. So this method of analysis or the methods of analysis that made use of Fourier series, Fourier integral fundamental and harmonics decomposition of a signal in to its components became known as frequency domain analysis.

The study of feedback amplifiers in the Bell system laboratory and else where because one was dealing with an amplifiers which where handling signals of this particular kind led to the development of frequency domain methods of analysis. Now the same set of people or people who were working in the another division of the same laboratory or any way who listen to each other or who received some of their education from amplifier people tried to apply or did apply these ideas to control system analysis.

Now just as Black's use of feedback in your amplifier was really strange or it was an idea which did not occur to anybody before him. Similarly, the use of frequency domain methods from control system analysis is also strange or at least I think that it is strange, why take the example of room air conditioning. Now what is the problem there as you said that if the environmental condition remains constant, if the people in the room sit there, so the amount of heat produced is such that it is taken away and taken care of by the cool air.

You can arrange the airflow and the air temperature appropriately in that case the temperature in the room will remain constant. You do not even need feedback but you need feedback because this is not what is going to happen out side temperature going to change people will go in, go out, come in there could be some lights being turned on, turned off power supply voltage could change so and so forth and so the room temperature will not remain constant and therefore you introduce feedback, feedback element call thermostat and so on.

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Now where is the periodic phenomenon here out side temperature will change but it is are going to change very sinusoidally, if one is talking about change the during of few hours, in a few hours this temperature is not going to vary sinusoidally even now over the day night cycle the temperature variation is not sinusoidal, people coming in going out, other sources of heat being turned on and off, power supply voltage changing there is nothing sinusoidal about these phenomenon. So there is no reason to use the sinusoidal function, the sinusoidal function simply does not occur. So can techniques of feedback amplifier design which were based on sinusoidal analysis or frequency domain analysis can they be used at all. Well it turns out that if the system that you are studying is linear, time invariant again some these terms you already know but you will take a look at them more carefully later on if the system is linear, time invariant then it can be studied using the sinusoidal of frequency domain analysis even though the input for the system may not be sinusoidal at all or may have nothing to do it any kind of periodicity.

So that you would not normally think of using Fourier series or Fourier integral as a tool of analysis. So because of this in the 1940’s and 1950’s and this continued for quite some time frequency domain methods of analysis of control systems had become very common place and had become really one of the most important of the analysis tools for control systems. One can look at the books which are published in that period, one will see that this was the case earlier what did people do? I mentioned James Watt and his governor which was studied by Maxwell or Airy’s problem of moving the telescope where it was continuous motion of the telescope as the stars moved in the night, no periodicity there during the night, how did the analyze the behavior of the control system of the system under control and the methods of controlling it.

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Well they used differential equations Maxwell wrote differential equations, Airy wrote differential equations. So the method of analysis used before Black's invention and frequency domain analysis techniques being applied in control system design, the differential equation approach was the one that was used. I mentioned earlier some work on steering of ships this was done by mathematician Minorsky in the 20's, 1920's and he use differential equations not Fourier series, Fourier transforms or ideas which led form there to some other ideas such as transfer functions. Again something which you probably already know if you have studied amplifiers but we will again take a look at it more carefully little later.

So now such things are found in Maxwell analysis or Minorsky analysis and in fact before the second world war there were lot of control applications, what were the major control applications or problems in the industry or going to back Watt's time speed control was one when electrical power finally replaced in most case, steam power, the use of motors as prime movers you can think so speed control of motors of various kinds of the DC motors to start with AC motors such as the induction motor and so on. This was one major area the second area in electrical engineering was in connection generating power generating systems or generating stations.

As I mentioned earlier voltage and frequency are the 2 important parameters of an electric power supply system. The power supply system whether domestic for domestic use or for industrial use should produce a constant voltage, the constant purely sinusoidal alternating voltage of a particular RMS, root mean square value and of a particular frequency. Let us a 50 hertz or 50 cycle per second and 230 volts RMS, pure sinusoidal voltage. This is what is desired in practice, as we will know the voltage can fluctuate typically in the evenings, the voltage goes down, you say that the power supply system is getting loaded the frequency also can go down at the same time your motors will run at a slightly lower speed some devices can have some problems the ideal is constant frequency constant voltage and good waveform, sinusoidal waveform.

Now all this have to be done with change in the load in the evening people will turn on their lights in summer they will turn on their fans industry will start some process, will stop some process industry is run for only 1 or 2 shifts obviously, it is going to be the load that particular industrial load is going to be switched off electric locomotives when they pull trains changes keep on taking place in the rush hour you will have more trains in the early morning and late night hours you will have fewer trains.

So there will be less load on the railway system these are all environmental influences which will affect the voltage and frequency and sometimes even the wave shape of this supply voltage that is produced. So this was a major problem and it still continues to be a major problem maintaining continuity of power supply of course is even more important but it is cause by very often by over load as you now or by accidents or faults lightning striking or surges or short circuit and things like that.

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So on the electrical side motor speed control and generator voltage control, voltage and frequency control were the two main problems in the early decades of the 20th century 1900 even going earlier, what are the other control problems in other areas of engineering. Chemical engineering was becoming of importance and significance and chemical processes required to be controlled, you are studying something you are mixing things, you are boiling things, you are heating, cooling, what not? A lot of these actions require maintenance of temperature, pressure, concentration of particular chemical and so on. Of course along with chemical engineering I should also talk about metallurgic process is production of iron and steel and other metals I mentioned the steel rolling mills and things of that kind.

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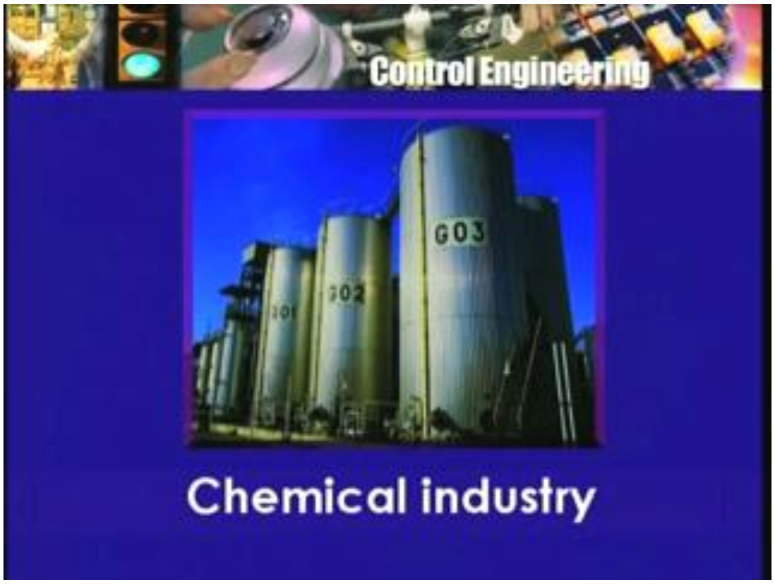

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So general production process industries, production of cement for example is a complicated process that requires control at various places and at appropriate times. So in general of course they are referred to as process control but in the 1900 with the discovery of the use of components of crude oil, the auto, cycle, the petrol engine, the diesel cycle, the diesel engine and it is increasing use chemical process industries in particular refining of crude became a very important industry and therefore there were a lot of control problems there which people looked at. But they did not use any frequency domain ideas any sinusoidal analysis simply because nothing of that sort was taking place there.

Another engineering branch which was picking up was aeronautical engineering and in fact right from the beginning there was control problem making something take off was not very difficult people had done it before the Wright brothers but keeping it going and keeping it going studiedly and ensuring that it will not suddenly hit the ground and come to a sorry end that was the difficult thing and it led to a lot of work of course mechanical kind of ingenuity if one looks at pictures of Wright brothers aircraft and compare it with today's aircrafts, one can notice difference immediately, the shape this, the wings in particular the propeller which has more or less disappeared now you have jet engines.

So there where a lot of control problems and there are still lot of control problems with aircraft flying. So that was another major area requiring attention and once again nothing sinusoidal there. So in all most all of these branches of engineering the tools that were used before the 1940's they are not frequency domain tools but they are what what one could called time domain tools that is one looked at what was going on in time not worrying whether it was sinusoidal or not.

So these are called time domain methods of analysis and basically they require us to look at differential equations and it is not new from the time of almost from the time of Newton, differential equations were being written for motion. For example, for motions of planets of course there was some special aspects of this approach or methods I said that the primary reason for feedback is to take care of parameter changes disturbances and so forth.

So for example looking at the air conditioner system how would one study it of course the outside temperature as I said does not vary sinusoidally it varies slowly say from early morning to noon and late afternoon the temperature may keep rising fairly, slowly. But for the purposes of analysis one could think of a sudden change or what is called a step change, one talks about the step function. So what happens if the ambient temperature is changed suddenly that is all of a sudden we introduce in to the room a large amount of heat how will the thermostat react to it, how long will it take we bring the temperature back to the original such things became significant and important.

Of course in place of the step function one could have a slowly rising or slowly falling or decreasing variable and therefore another function what is it called, it is called the RAMP function because if you plot it it looks as if it is a RAMP or a slope over which you may carry something or roll something. So step function RAMP function response to these were the methods used for the study and design of control system before the frequency domain methods were introduce in the 1940's and 50's. Subsequently of course people have gone back to the time domain methods for various reasons, frequency domain methods sort of ran out of steam for some time then people invented a few more things differential equations after all were not such terrible creature's, engineers had become familiar with some mathematics of differential equations and more importantly the digital computer was becoming available at an affordable prize.

Now of course the digital computer is a peculiar device in does not use sinusoidal signals but it does not also use differential equations, today's digital computer at least. However, differential equations can be handled also without too much difficulty using a digital computer handling sinusoidal analysis is no less easy. So along with the frequency domain methods a number of time domain methods have also been introduced from 1950's and 60's onwards many of them of course have not yet found a place in the under graduate control systems course partly because we cannot study everything. But in our lectures here we will spend some time on the time domain methods as well and a little less time on the traditional frequency domain methods, along with the method of analysis goes something else which is important in control system study and design and that is what are called specifications, if you want to design something usually there will be several solutions.

First of all of course even before you a think of a solution you must say what you want pick the case of the air conditioner once again you may specify that the temperature in the room should lie between as in our example 26.9 degree Celsius and 27.1 degree Celsius that is 27 degree Celsius plus minus .1 degree Celsius. Even if the outside temperature goes up by 10 degrees or the source of heat of a certain size or capacity is turned on in the room and so on and so forth. So this my specification or spec as it is called.

Now design for me a control system here is the room, here is the air conditioner go ead and design a control system and if there are 2 designs or more than 2 designs which meet the same specifications then as is the case in India and many other places also one chooses the system that is least expensive. Of course some times after you buy the least expensive the system you incur a lot expense on it or there are hidden expenses and in today's world of course there all kinds of influences at work but there must be specifications any time, anybody buys something using some body else's money. There will be some specifications, then you will get quotations and then you will select same thing here there is a system to be controlled, you put down specifications, you put down what you want the control system to do that is a system which will be used to control the given system, what is it that is expected of it the specifications, the design specification.

Now they are of course dependent on the particular control application that is the particular system that is being controlled and so the specifications go with the system but they can also go with the method of analysis that is used to study and design the control system. For a speed control system let us say a speed for a milling machine or rolling mill or whatever you will say that the speed should not vary more than plus minus such and such percent. Even though something else may vary the load may vary from no load to full load. All the machines in the workshop are operating laths, milling machines, drilling machines, what have you full load on and no load or very little load I have a main motor which drives a shafts from which I take power to the various other machines this was the old style today of course that is no longer the case every machine may have its own independent motor and so you may say from no load to full load, speed should not vary by more than such and such percent.

So this is a appropriate design specification for the application where it is required that the speed should remain constant but it will not remain constant. You have to allow some variation you might specify the percentage variation it is sometimes called percentage regulation that is the term that was used in connection with power supply voltage and one talked about voltage regulation plus minus 1 percent regulation meant that the voltage could vary within plus minus was 1 percent but not more than that.

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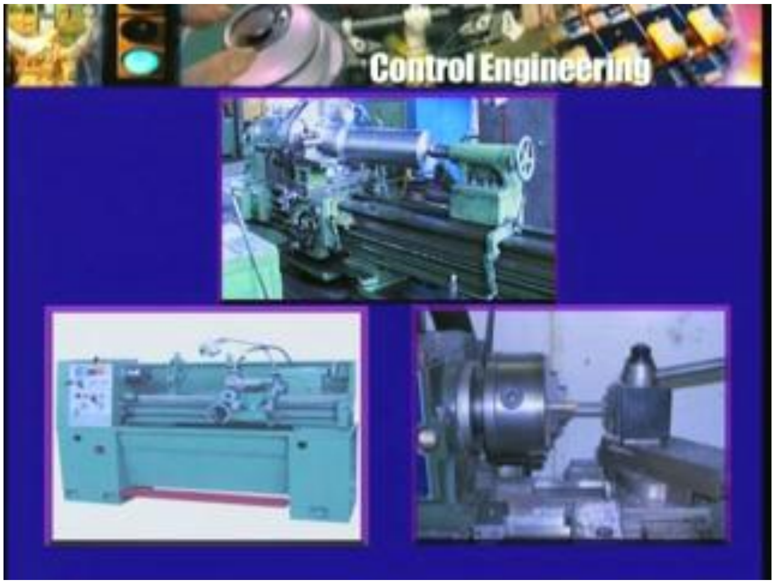

So if you had a regulated type system then this specification one of this specifications would be this percentage regulation or you can also think of it as accuracy of some kind the speed should be such and such it is going to deviate from it slightly. So how much inaccuracy can you tolerate. I mentioned another thing earlier namely a load is suddenly switched on or switched off corresponding to a step function input, then there is another aspect that comes in to the picture when a change like this takes place. Let us the outside temperature change suddenly the room temperature what will happen to it or the load on the motor is increased suddenly then what will happen to it or in a different situation you may decide that the desired speed needs to be changed the room temperature instead of 27 degree Celsius now I want it to be a little cooler, say 25 degree Celsius. So I change the a thermostat setting from 27 to 25.

In industrial applications temperature setting may have to be changed the pressure setting may have to be changed for a different problem and so on and so forth. In the case of an aircraft you have to change the altitude or the height at which the aircraft is flying. So with a sudden change in input reference input, you would like the output to also change as quickly as possible. Once again you may want things to happen but they will not just happen. So you have to allow some flexibility so natural specification is that there will be a time delay or a time lag. The thermostat setting has been changed but the room temperature will not come to the new value till some time has elapsed and this time is known as the settling time and so this provides one specification the system should settle down to the new value in not more than say 10 seconds or 5minutes depending on the particular application, with chemical processes the time may be little longer.

So settling time is one specification. We will see again I am telling that will see but we will really see later on that with some control system design when the set point is changed or a step input is given to the system some oscillations may be produced. So these oscillations die , so they do not stay there like an oscillator but they are produced. Now that may be undesirable you may say that there should be no oscillation or you may tolerate the oscillations a little bit after all the room temperature is going to fluctuate between 27.1, 26.9 so I should not be averse to tolerating some oscillation. So one talks about overshoot and undershoot and one may put a limit on the overshoot and the undershoot.

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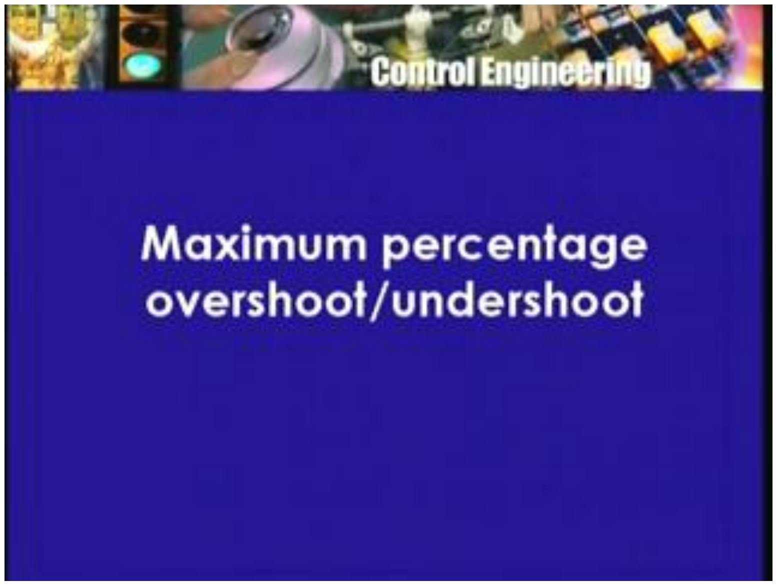

So that gives you another performance or design specification, maximum percentage overshoot or maximum percentage undershoot. Let us say you may tolerate up to 10 percent or 20 percent of overshoot and undershoot no more. The third specification for this kind of application would be what is called the rise time settling time is okay but I do not want it to be too slow either once again depending on the nature of the system and the order of the system there are variations that are possible and one can design different control systems which achieve different things. For example, you may want a rise which is as fast as possible however, you cannot have this rise unless you are willing to admit some oscillations as I said there could be some oscillations.

But instead of a slow and steady rise to the desired value or change to the desired value which after the settling time is very close to the desired value. You may want the rise or a fall as a case may be which is quick but the system does not quite settle at that time, it may continue to oscillate for some time that is okay but it should reach I will say 95 percent of the desired final value within a certain time.

So one may arrive at a rise time of let us say 1 second for the final value being approach within say plus minus 10 percent or plus minus 5 percent where as the settling time could be 10 seconds, for the actual value being very close to the desired final value. So for regulator type systems these three specifications are all most obvious consequence of what is it that the regulator supposed to do, settling time, percentage overshoot, maximum percentage overshoot or undershoot and rise time. There are no frequency domain ideas here there is no you are not going to give a sinusoidal input, obviously you could or you could at least theoretically when you do an analysis think of a sinusoidal input but it is not natural to the problem where as in the case of the amplifier the situation is quite different the feedback amplifier.

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For example, the amplifier works with or the speech amplifier or amplifier in a telephone or in audio communication system works with audio signal which has certain features one thinks of one talks about harmonics, sinusoidal components and so on and so there is a corresponding natural concept associated with it called frequency response of the amplifier the amplifier gain is not the same independent of the input frequency at different frequency is the gain and also there a phase shift that is produced they could be different for a good amplifier. For an ideal amplifier the gain should be the same at all frequencies going all the way from very low frequencies or very close to DC to very high frequencies of course how high depends on the application in the case of audio may be say 20 kilo hertz is good enough and on the low frequency side may be a few hertz or even 20 hertz may be okay.

So here is a design specification for an amplifier the gain should be constant, should not change with frequency over this frequency range. Now once again it is not possible to have an absolutely constant gain therefore one will specify the tolerance within which the gain should be constant similarly, you may talk about the phase shift. So gain and phase shift verses frequency these are very natural specifications for an amplifier and in fact people realize that by using feedback you can change these aspects of the amplifier an amplifier whose gain was not as constant as was desired earlier by changing it, by using feedback, could be made into an amplifier whose frequency response is more constant. In fact this is one of the side benefits of feedback Black had not thought about it he was only thinking of stabilizing amplifiers but as I said earlier feedback has other effects.

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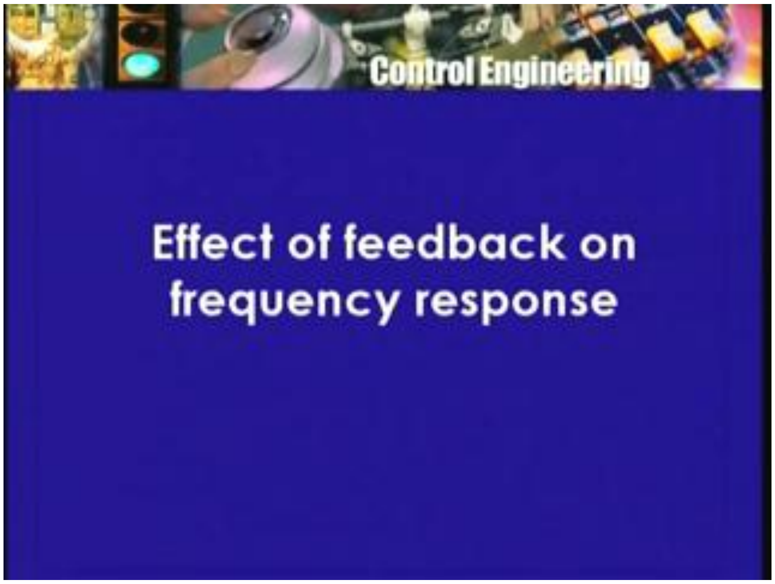

So it has effects on the frequency response of the amplifier and once again by careful design you can have a improvement in the frequency response of the amplifier. So if I want to design a feedback amplifier, this could be a specification and when one uses frequency domain methods of analysis then one normally natural talks about term which involve a relative frequency, gain, phase. As a result as a result of the work by Bode and Nyquist concepts such as frequency response of a feed back control system, gain margin phase margin and others came in to use and we will take a look at them, but we should remember that they were natural for a particular setting namely the setting of an amplifier they are not 100 percent natural for a control system situation.

I have been talking about regulator systems, at the moment as far as specifications are concern what about servo mechanisms or follow up control systems such as the gun control system, the gun should follow the target or a preset course should be followed by an aircraft what kind of performance specification would one think of especially when what is to be followed is not known beforehand, I do not know how the enemy aircraft of the target is going to move what maneuvers it is going to perform the simplest course specification would be that well the orientation of the gun it may not coincide exactly with the target position but should be within such and such tolerance that is a difference and this case it can be called an error justifiable because the gun should be pointing at the target however the gun cannot be moved instantaneously.

So there is an error and if you short this fire the shell it will actually result in an error that target will not be hit and something else may be hit, get hit. So one will one naturally talks about error as the difference between what is desired the signal to be followed and what is actually being achieved and people realize that there is nothing like you know step function the target was not likely to suddenly jump up or in an instant turn around and things like that. But you would have the target moving for some time you would have the signal to be followed for some time over what one calls an interval of time and there will be error taking place of course all along this hopefully the error will be reduced as the system proceeds in time but there could be error and therefore one could say that all right, a system which over a given a interval of time has a lesser error then another one would be preferred cost being equal.

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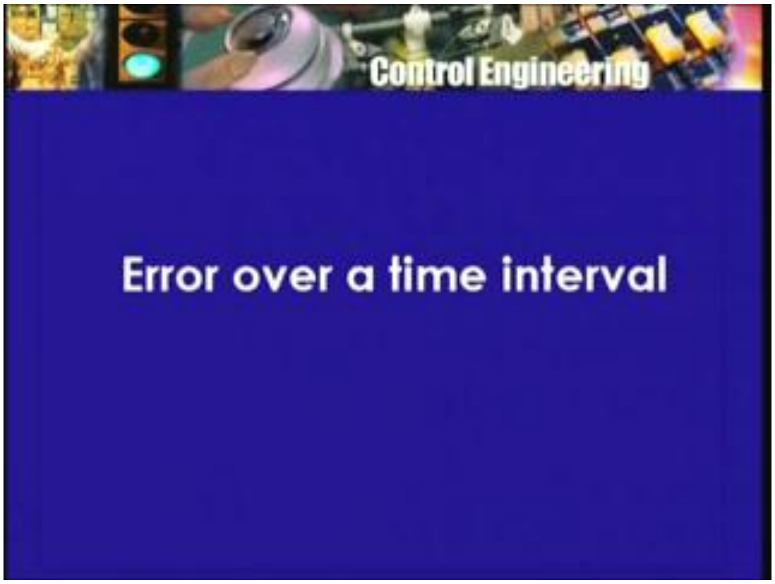

So this led to some performance specifications which involved what is called as the integral squared error criterion or specification. The error could be positive or negative, so you get rid of the sign problem by squaring it was one way of doing it the error will be there not just at one moment but may continue you are looking at the error over a whole period of time, 1 hour or whatever. So you integrate the squared error and that sort of gives some idea of how good or bad your control action was and of course this give rise to the idea of not only reducing the error but trying to find out what could be the minimum error that you could achieve and this gave rise to what are called optimal control problems or optimization problems for a control system.

Interestingly this was also going side by side during Second World War effort and naturally the frequency domain methods which were being, which had been developed for amplifiers and which were being use for control system design became applicable or where applied to this problem also. The problem of servo mechanisms or follow of systems with integral squared error as something which was to be reduced or which was specified an upper limit was specified again during the course of analysis one finds that somethings are convenient.

So the concepts of what is called steady state error also was introduced the outside temperature changes suddenly but remains then constant at a new value is the air conditioner able to cope up with the increase in the outside temperature and bring back the temperature to the old value may be after a settling time or is there going to be a steady error that is as time passes you do not quite reach the desired value, not within the original tolerance zone. So in that sense there could be steady state error, error which persists even after a long time and not what is called transient error while changes are taking place there could be of course deviations, unsatisfactory operation but all that may be transient if it disappears after some time then its transient but it may not be transient, it may persist.

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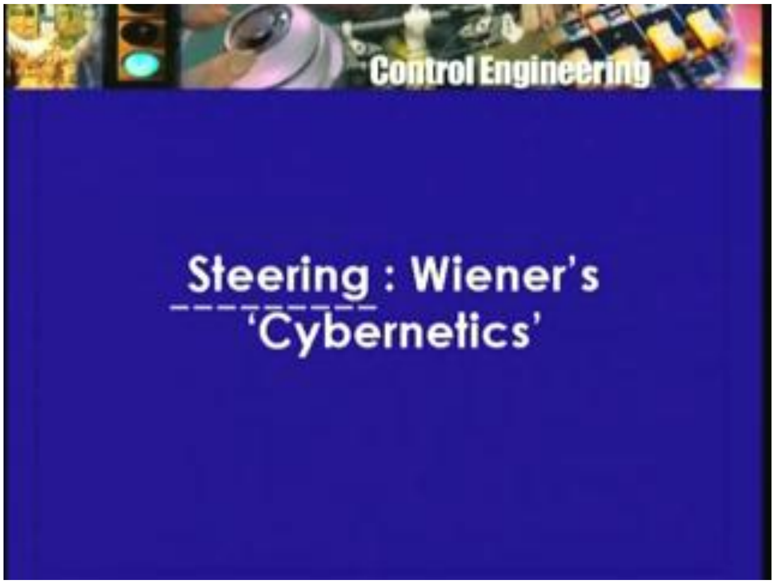

We will see that for some systems and for some type of control this can happen, there can be a steady state error but as I told you earlier the word error has to be used carefully and many text books do not deal with this carefully and I will point out to you what are some of the errors in the treatment of this topic of error in a control system. We have taken a look at 2 kinds of control systems. The regular 2 type system and the second one the servomechanism follow up or tracking system or which could also be called a system which involves essentially something like steering and indeed Norbert Wiener one of the key persons during the second world war effort in the USA introduced a term or a name for a subject which uses the Greek word corresponding to the idea of steering it is called cybernetics, there is a Greek root in this cybernetics or strictly, it is not cyber but cybernetics which is the Greek word for a person who steers a boat or a ship once called a helmsmen or the steersman and so the science of steering of the study of steering was called cybernetics.

So if you want the fancy name for control systems and you can use the word cybernetics and today of course the word being used in some different context all together one talks about cyber space without really knowing what that word cyber meant originally, simply because your computers and communication systems and wireless and this that and the other they have started using the word cyber but its original meaning was quite different dealt with this problem of steering. There is another class of control systems or another class of control situations which we will look at now.