Product Engineering and Design Thinking
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Module - 07
Product Complexity, Affordability, and Design Thinking
Lecture - 31
Tolerance Design: Taguchi Robust Engineering

Welcome back participants. We are continuing with your session on Product Engineering and Design Thinking and today the 1st lecture of module 7. The module 7 is on Product Complexity, Affordability and Design Thinking and this lecture is on Tolerance Design which is based on Taguchi's Robust design and Engineering approach.

As I indicated to you earlier that this Taguchi method is a well known method and there are several resources available and in my last lecture, lecture number 30 I have provided certain links also for those. So, up to the parameter level design there is not much difficulty because there are plenty of resources you can go to any there are many other materials books also is there.

So, whatever you intend to learn about this parameter design part you can and rather easy. What I have observed may be you also will observe if you do some search that the tolerance design practically has not been addressed practically it is very scantily available and therefore, how to proceed is not very clear to the users.

So, I have taken that up as an exclusive lecture session and therefore, today we will focus only on Taguchi's robust design methodology part which is tolerance design. This is very important particularly for complex products where so many factors and components and variables are involved and when the performance is being affected through by the you know variation in several inputs and it is very difficult to decipher which one is that unless we have a systematic method like tolerance design etcetera.

Tolerance design is done only after parameter design because once the parameter is decided that is at what level the effect of this noises or the variants variations would be minimum and then at that point also, we need to optimize. In the sense that at a given point say at a given temperature say 50 degree centigrade whether it works best between 55 45 to 55 degree centigrade or 48 to 52 degree centigrade that would give the best result.

So, tolerance design becomes very important for that and at that level. So, product engineers, product developers, designers they use this method so I am only trying to fill that gap which is practically non-existent in as a tutorial video material and would attempt to cover that.

But let me tell you I also have put a reference here when I chose an example. The example is not same, but a similar problem has been dealt with by Philip J. Ross in his book that I will discuss, but they are also there certain results are placed, but the intermediate steps perhaps will not be so much detailed as you see.

Be that as it may, so I start from here with the short preamble stating that our job is also to address this complexity of product and that we for that we need to discuss tolerance design. Hence, without further elaboration on this I would like to go and go to the slide called concept covered.

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So, now here what I find is what you would see is that the focus is only on tolerance design and we will discuss the approach and this approach we would actually explain, explicate with a with the help of an example, example problem and then we would go to the steps.

But of course, some of the steps are involved are you know are part of say statistical methods etcetera where I have given the glimpse, but; obviously, if you think that you need a little more learning on that you can consult any book on say for example, ANOVA, ANOVA we have used analysis of variance. So, you can use the learn that from any such a NPTEL or say for any YouTube lecture or say any online lecture or say from books and etcetera those are easily available.

But then I have just given the glimpse of it also, so that you know how to connect. But for obvious reason because we are discussing product engineering and hence, we will not be able to go much into the details of all statistics, but these are simple steps and it is not very difficult for you to understand. However, I have placed it in very systematic step wise method that will be rather convenient for you I suppose.

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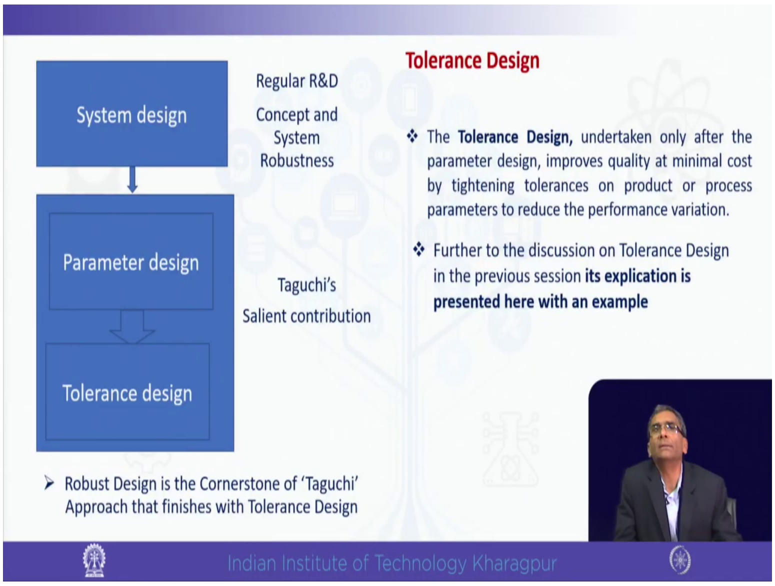

This already I have told you, but to start today's discussion I am giving this reference once again that Taguchi proposed the you know robust design methodology which starts with system design and but Taguchi's major contribution is in parameter design and tolerance design.

Here we have already discussed parameter design earlier; we will focus only on tolerance designs today. The here as I said it is presented with an example and the preamble already are discussed in the last lecture. The major there are various other aspects at the introductory stage which has been discussed in lecture number 30. So, I would not repeat them here if you want you can go back go to my presentation lecture number 30 and find what was the content. It is the lecture number 31 just the previous one.

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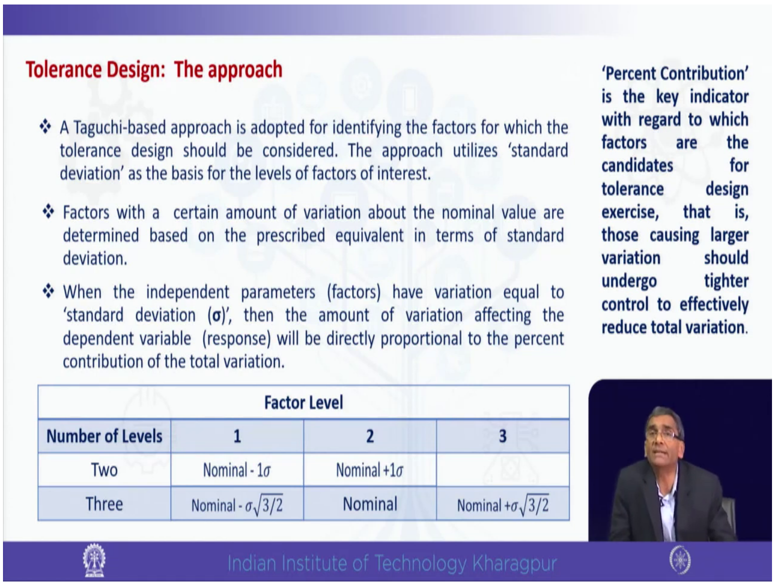

Here I would just give you a glimpse of the tolerance design as I said it is Taguchi based approach by it actually works on the principle of standard deviation or which normally, we express as sigma small sigma. Factors with a certain amount of variation about the nominal value say a nominal value of a dimension maybe say in millimeter it is an and so what is the range? It will have a span say range from minimum to maximum as we see as we know in a tolerance this thing.

Now, to assess the effect of variance it is not exactly the limit or what is called that USL LSL upper specification limit, lower, specification limit based, monitoring and tolerance stacking it is rather it is not that it is rather to check the effect of variance and meeting of the inputs on the final product the output. And here our purpose is to mitigate that by adjusting or tightening the tolerance more specifically.

So, to what extent we should we title should we and that rationality because making it too close may increase the cost and demand on resources which perhaps is not so much required. So, what is the optimum level? How much is we can tolerate that is what we try to find out from here.

Now, as we have discussed already about the concept of level in Taguchi design. So, if it is a two level problem two level consideration or two level design two level design planning then the lower limit is set as nominal minus 1 standard of deviation and the maximum is nominal plus 1 standard deviation; that means, nominal plus minus 1 minus sigma and that is a nominal plus sigma.

However, if it is a case of say three level then a three level is a that is a something called max min, mid and min maximum and minimum these two extremes and the midpoint; midpoint which we called here the nominal for nominal value. Like say when we say a pipe diameter of a pipe is 25 millimeter. Now, that is a nominal diameter does it means that all pipes will be 25 millimeter no that is a nominal diameter, but then it may vary between say 25.5 to 24.5. So, that is the variation.

So, nominal diameter if I have to ask, I will say it is a 25 millimeter diameter pipe. Now, so, here the formula for this as you would find in the handbooks at other places of etcetera that the minimum is nominal minus standard deviation multiplied by square root of 3 by 2 and maximum is a nominal plus standard deviation into square root of 3 by 2.

These are these have already been devised and it is universally acceptable accepted and it is used by the practitioners and everybody. So, and the mid value is nominal as I said, so this is the fundamental understanding. Here the important point is that in tolerance design how we define which out of so many factors or components involved rather all components are not equally responsible for the deviation or variation in the outcome.

So, which are those on which the outcome depends is the first thing to be found out. So, who which are those candidates on which we have to apply tolerance design in particular. There may be some other factors where which has very limited effect on minimal effect there, we need not do anything because it is not contributing to the outcome.

So, identification and controlling of those factors identifying those factors are important and that is done through a concept called percent contribution which is the key indicator with regard to which factors are the candidates for tolerance design exercise. That is those it is written here also on bold on the right side you can find that is those causing larger variation should undergo tighter control to effectively reduce total variation. So, now we have made the entire preamble the background

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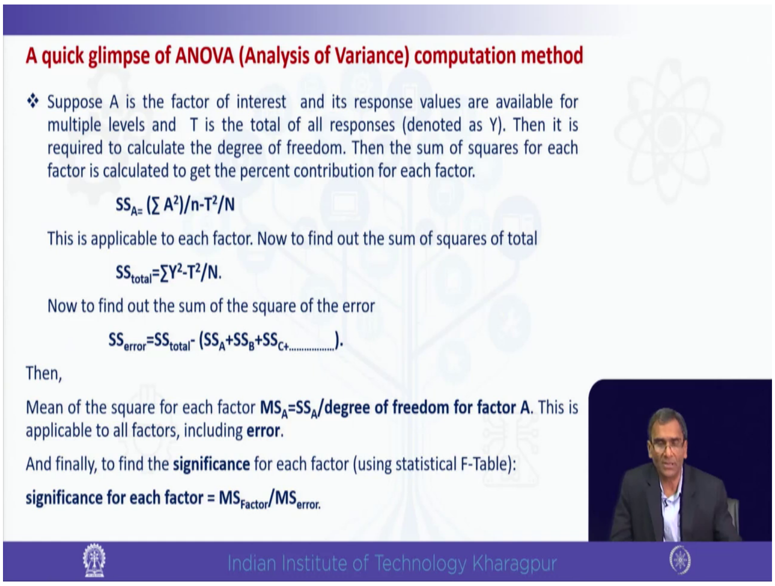

Now, we will move on to a glimpse that I just in the beginning set analysis of variance that is a that is a calculation which perhaps you have already seen while doing parameter design or you this ANOVA you will find plenty of books and materials learning ANOVA is not difficult. That means out of ah ANOVA is basically analysis of variance that is the source of which affects the total variation how much that is the analysis.

And after see there is a total output and we are explaining trying to explain the contribution of each factor. Suppose there are five factors. So, what is the extent that five factors are contributing to that and when we are a comparing that with the total variation, we find that there is a gap which is unexplained where we cannot say that ok yeah we can say if there are five factors A B C D E, as contribution is this BS contribution is this, ES contribution this and so on and so forth.

But still the 100 percent is not complete there is a small part which is still unexplained that that gap is called error. So, here we need those concepts and this the treatment requires a statistical computation where the sum of squares concept and there is also a concept of say your means sum of squares.

So, so these are the things that is error as I said is sum of square of total minus sum of square of individual factors which are the components in this case. And mean of the squares for each factor is determined and there is a concept called degrees of freedom. So, it is a statistical degrees of freedom it has nothing to do with. So, called mechanical degrees of freedom that it is having a three-dimensional it is a statistical.

So, any standard preliminary book on statistics you can consult because see these we are dealing from the product engineering perspective. So, I would imagine that your carrier would be in product engineering that is the main thing, product design product development product engineering and whatever say other materials say statistics.

Because I hope you would appreciate that entire statistics whatever is used here from the very fundamental, we cannot come up to this because otherwise those will be different stream of lectures.

So, one stream of lecture will be ANOVA one stream of lecture will be on some other statistical methods. So, here I would suggest in case it is I mean there are so many materials available you can go to any tutorial videos and you can run it. And here therefore, there is a thing called significance test which as I said which factor is important and it becomes a candidate for tolerance design not all factors.

So, how significant is that that it becomes a candidate this is the significance is identified through a test called F test, a Fishers test. So, it is that is why it is called F test which is taken as the ratio of ah mean of the square for the factor divided by mean of the square of error.

Error, I have already told you what is it. So, this is the basic glimpse I am not discussing the entire ANOVA process here it is not possible also because the course is on product engineering and not on statistics per se, but then whatever the statistical input required I am introducing you to that. So, that whenever you find it interesting or more importantly when you find that you are needed to use it then you can go to those and quickly learn it

Because these are interesting and advanced methodologies for dealing with complex products. In fact, the more these things are done one would find that without any major investment by tweaking or a by adjusting and controlling these values would give much improved result.

And therefore, the better quality at same or lesser price can be made available which addresses also the affordability issue. So, that is why we have chosen to deal with it in this category which is complex product and with affordability aspect alright.

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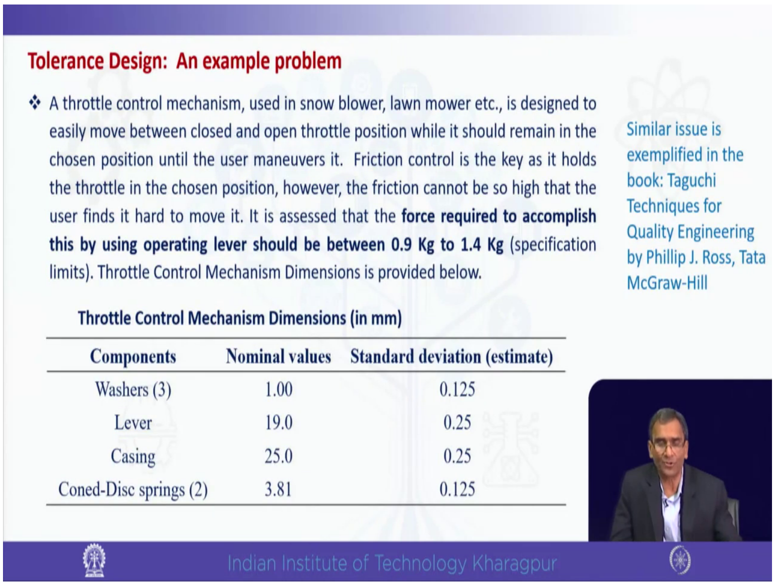

So, now, we proceed with that example. This example is self-explanatory and here we would deal with a throttle control mechanism. Throttle control mechanism is a is a kind of a product which is used in many places it is used in snow blower, mist blower, lawn mower. So, there are several of in an automotive of course, there are throttle control which actually controls the fuel controls the air mixture and therefore, the you know best outcome in terms of power generation and speed and all that happens speed particularly.

So, here are such a throttle control mechanism which is to operate that the user would maneuver and there is some force required to adjust that lever to get that particular level of throttle. Like when you press the accelerator in your car you apply certain pressure a lever pressure.

So, here also that lever pressure is applied and the according to the ergonomic convenience and the convenience of the best you know performance of the product it is set at that 0.9 kg to 1.4 kg minimum and maximum load level would be the best and that is the specification therefore.

So, here in that product on the left you would find that this at the components 7 components are used in all. In 7 components means 3 are washers, 2 are coned disc springs and lever and casing. So, in all there are 7 components which have been mentioned here washer within bracket 3 means 3 washers are used coned disc spring within bracket 2 means 2 coned washers are used C 1 and C 2 washer W 1, W 2, W 3.

So, W 1, W 2, W 3, L, C and C 1, C 2 makes it 7. Now, here for each we have presented the nominal value all are in millimeter on which is written on the top. So, here the idea is that the friction control should be such that when I fix it the you know the control it stays at a particular point and does not move away. So, easily, but again it should have been too hard that when I intend to move, I can also move it easily or any the user can move it easily.

So, the friction should be enough, but friction should not be too hard you understand the challenge. So, therefore, that there comes the tolerance design and the range. So, here the range is 0.9 kg to 1.4 kg. Now, here you will see the here it is driven by the standard deviation as I said. So, the nominal values to start with as it was felt that the standard deviation would be 0.1 to 5 in case of the washers and coned disc spring; however, it should be 0.25 for the other two the lever and the casing.

We will see we will if we choose this whether it satisfies the purpose. If it satisfies fine with this if from our experiment, we will find that 0.9 to 1.4 kg is being made that is fine or else we have to adjust those values or the deviation values which actually is the control of tolerance. So, the deviation values are readjusted and the experiment is rerun to see whether now it is within the desired range or not.

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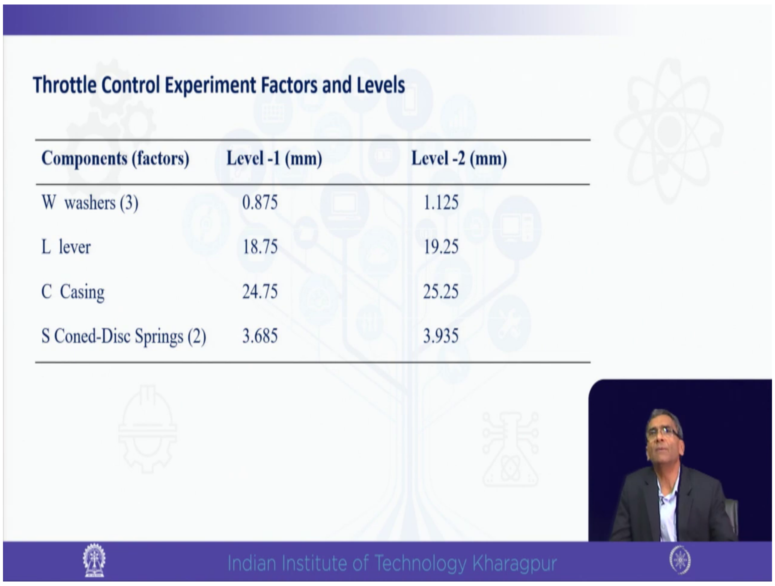

So, now we will proceed. So, here we have already given that those data that is level 1 and level 2 that as you have seen that the say for example, it has been done for all cases the nominal value is 1 and the standard deviation is 0.125. So, if it is a plus nominal plus sigma on the maximum side and nominal minus sigma on the minimum side if we are taking 2 level, then it would be 1 minus 0.125 as minimum and 1 plus 0.125 as maximum let us see.

Here you see that the 1 minus 0.125 which is 0.875 is on the level 1 or the minimum 1 or and the higher level is 1.125. So, similarly for it has been done for all components the minimum and maximum where for lever and casing it was 0.25. So, you can see the nominal value for lever was 19. So, 19 minus 0.25 is 18.75 and that is 19.25 of the higher side. Casing was 25, so it is 24.75 on the lower side and 25.25 of the higher side. Similarly, for only spring etcetera, so this is the minimum maximum values.

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Experiment/ Treatment	Lever Force (Kgs.)	
	Y_1	Y_2
1	1.02	0.99
2	1.03	1.05
3	1.16	1.12
4	1.14	1.11
5	1.01	0.99
6	1.27	1.29
7	0.98	1.01
8	1.28	1.27

Now, with this we run the experiment. The experiment here normally one experiment so, it is I said that there are 7 factors already component and there are 2 levels. So, it will be as we discussed earlier that it will be L 8 the orthogonal array. L 8 means there will be 8 treatment conditions, but the thing is here we could have just Y 1.

But why we have taken Y 2? Because often it is found that single value may be erodius. If 2 values are not closed then we can investigate if anything is gone wrong. So, though it is not mandatory to use 2 sets of data, 2 you know experimental runs, but it is always preferred that 2 experiments are carried out. So, that if anything by any chance I mean it is unlikely that 2 will go heavier at the same time, but at the probability is much less that is why 2 r often considered and that is what is recommended also.

So, here you see that 2 sets of values are taken for the same 8 experiment. Same means equal number of experiment techniques. So, 1 through 8 and the first set is giving the values as this based on the L8 or OA8 table which we have discussed in the previous slide. So, I do not want you to be burdened with that again. You can always refer to an OA8 in the parameter design in the lecture number 30.

Ah And obviously, I have to do justice with time. So, I would not bring the old slides over and over again to explain that, but you can always check what is way and that will be good exercise. This is way when we can just Google and find out what is L8 and you would see for yourself right away, right now in front of you in the in your laptop or computer or whatever or mobile phone.

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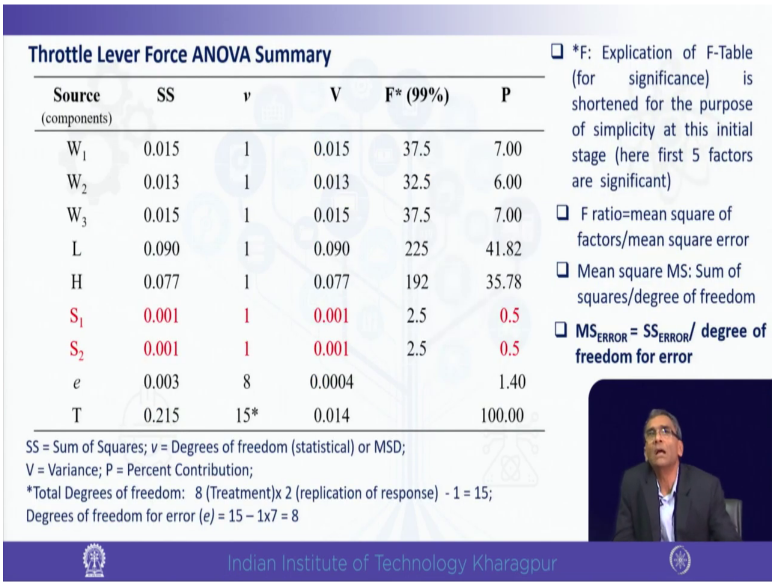

This looks like a bit complicated, but do not you worry it is not really. So, because I have already explained all these things the background theories are given. Here as I said that these are 3 washers W 1, W 2, W3 lever a casing this by mistake is H which should be C we will make the corrections here it is casing. So, whatever these values are this and so here what do we find that the sum of square values based on the data already provided is 0.15, 0.13 and so and so forth sum of squares etcetera that you have already got that.

Now, degrees of freedom 1 and total degrees of freedom since these are 8 experiments and 2; that means, total 16 and we know design of in the degrees of freedom would be that 16 minus 1 that is 15 which is at the bottom. So, total degrees of freedom is equal to 8 treatment into 2 replications and minus 1 is equal to 15.

Then the mean standard deviation or the called variant this variance. So, the variance is the sum of square divided by the degrees of freedom and you can see that those values here. And the F table the calculation I have already discussed and these are the values and there is a table called F table again I do not want to bother with you this is you Google and find these F tables at the different confidence levels.

So, here what do we see that except these two which are written in red have become significant. So, top 5 are significant. So, that that for that the critical values those which are above the critical values would be considered critical and that would be known from the F table. If you consult F table and the MS error divided is equal to the SS error divided by degrees of freedom for error we can find out.

So, far so good and now from here we come to the percent contribution. The percent contribution if you see 0.215 here and if we say that is a total and first one is 0.015. So, what is the percent contribution of washer 1 in this? So, it is 0.015 divided by 0.215 into 100 that is 7 percent.

Similarly, for washer number 2 it is 6 percent for washer number 3 it is 7 percent whereas, this lever and casing it is 41.82 percent nearly 42 and that is nearly 36 percent 35.78 to be precise. Rest are the values which are not high and they are not significant also and the error percent contribution also is very small that is 1.4.

So, from here we find that percent contribution of these two components this lever and casing are maximum and which constitutes more than 75 percent of the whole variation. Hence, we would try and see what we can do here rather more precisely that we need to tighten the tolerance on these two components like it was 0.25 for each.

Now, we have to reduce it and therefore, these two the red ones it is called pool that we are pooling and merging it with the error; that means, we are ignoring them and taking it as an error which does not affect as much. So, here this error degrees of freedom becomes 10 if we add these two red ones 1 and 1 and the total also get added and so we are removing the spring aspect of the thing and so we come to this new table.

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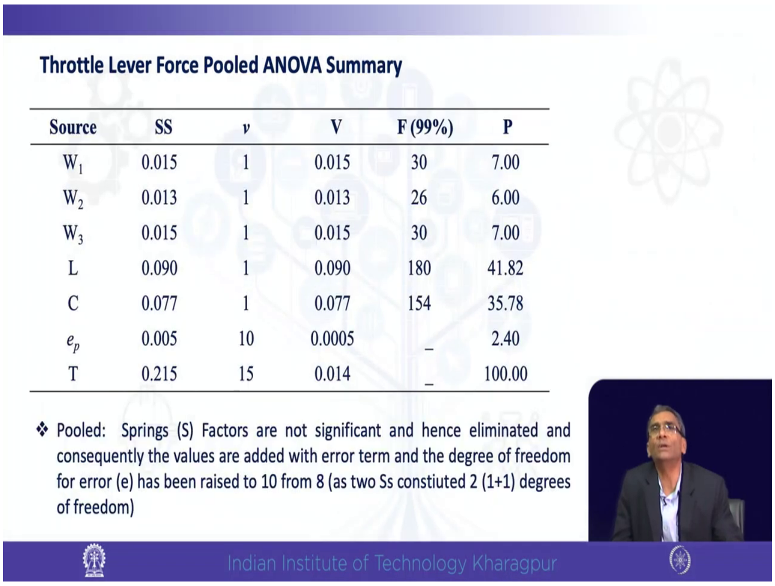

So, here we see the recalculate and we find that error has by combination it has gone up from 1.4 to 2.4, but we now are better focused with the dimensions and see what is happening here because we have merged that error term with the springs fine or the rather the springs are merged with the error.

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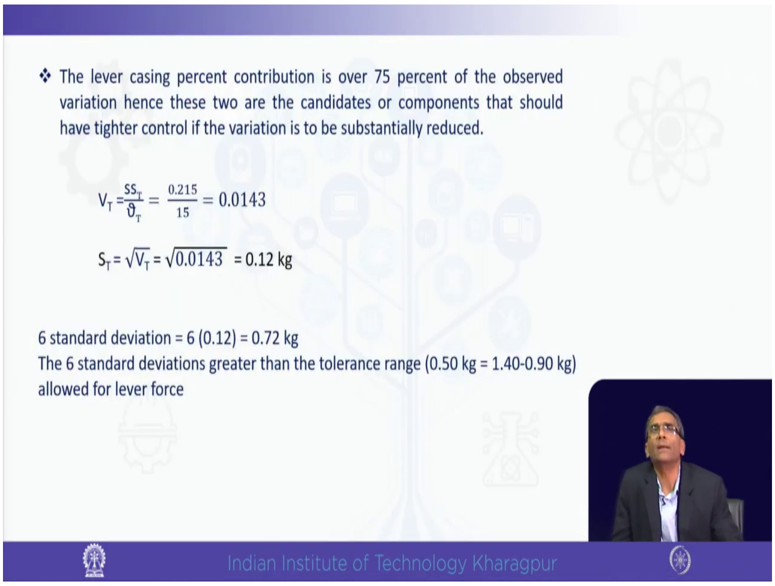

Here the equation is that the variance which is the sum of square total by degrees of freedom total and all these values are known to you already which is 0.215 divided by 15 that is 0.0143. Standard deviation we know which is the square root of the variance that is 0.0143 which is expressed in kg, so it is 0.12 kg. So, standard deviation now is 0.12 kg by is 0.12 kg is good enough for our work.

Question is how much is good enough? Good enough is our range is 0.5 kg because we are saying it is operable between 0.9 and 1.4. So, 0.72 is higher when we are considering that 6 standard deviation yeah 6 standard deviation plus minus 3 sigma. So, 6 standard deviation is 0.12. So, if we are multiplying with 6 it becomes 0.72 which is higher than what is prescribed or what is desired target value, so it will not work. So, what we do? We tighten the tolerance as I just said.

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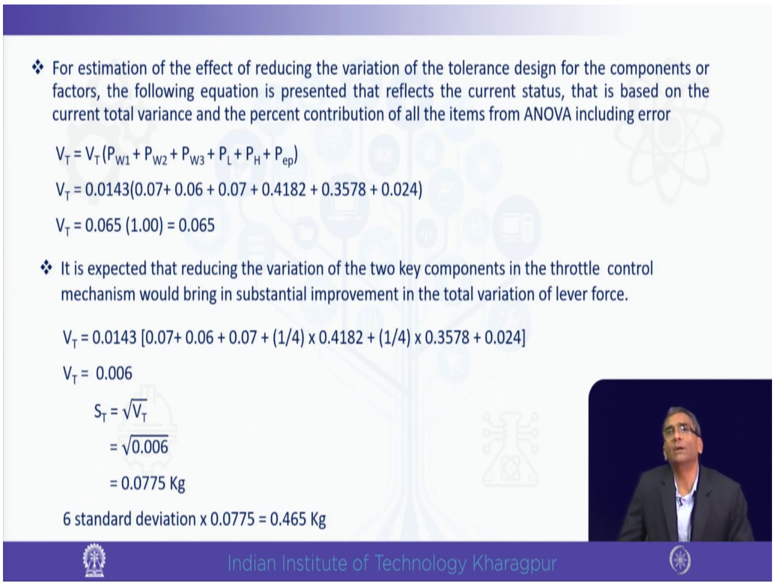

So, how do you tighten the tolerance? We make say I put a factor of 1 by 4 one fourth, it is to some extent you can call it a trial and error method. So, we multiply this those two only rest all will remain same those two only we are reducing the their influence on the variance. So, we will see what the variance becomes that for the just a minute for which one it was yeah for the lever yeah for the lever it is 0.4182. So, one fourth of 0.4182.

Similarly, for the casing it is one fourth into 0.3578 and the that 2.4 the error is expressed as here because we are removing that percentage thing here. So, it is 0.024 and from this we find that the value of V T is equal to 0.006 taking a square root of that would give us a standard deviation which 0.0775 kg. Now, 7 6 standard deviation of that 0.0775 kg is 0.645 kg.

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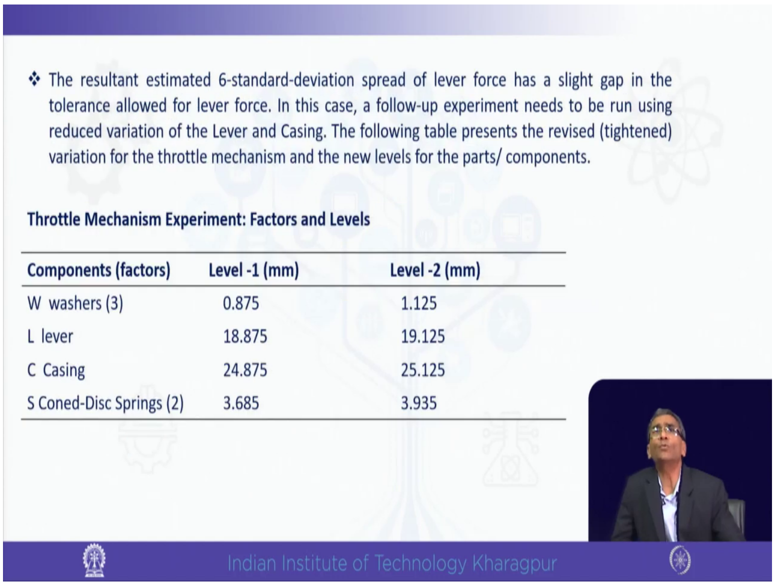

Now, we will see if that works now. So, here you see that the first and last were the same, but in the middle two the lever and casing we are reducing the range which was 18.75 to 19.25 we are reducing and we are increasing the lower level and reducing the higher level.

So, what we are doing we are attaching it. So, it instead of 18.75 it becomes 18.875 and 19.25 becomes 19.125 same is for casing thing. Now, what happens? We have to then with this new dimension we have to again run that experiment as I said again see whether it works.

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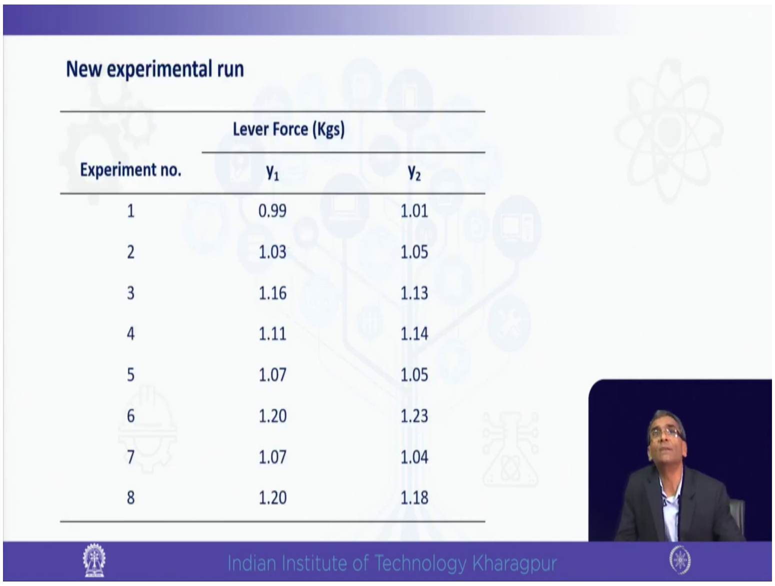

Experiment no.	Lever Force (Kgs)	
	y_1	y_2
1	0.99	1.01
2	1.03	1.05
3	1.16	1.13
4	1.11	1.14
5	1.07	1.05
6	1.20	1.23
7	1.07	1.04
8	1.20	1.18

So, again the new experimental run is done and these are the values. So, it is iterative process. Now, how many times you do no new information knowledge you require you only have to carry out the experiment.

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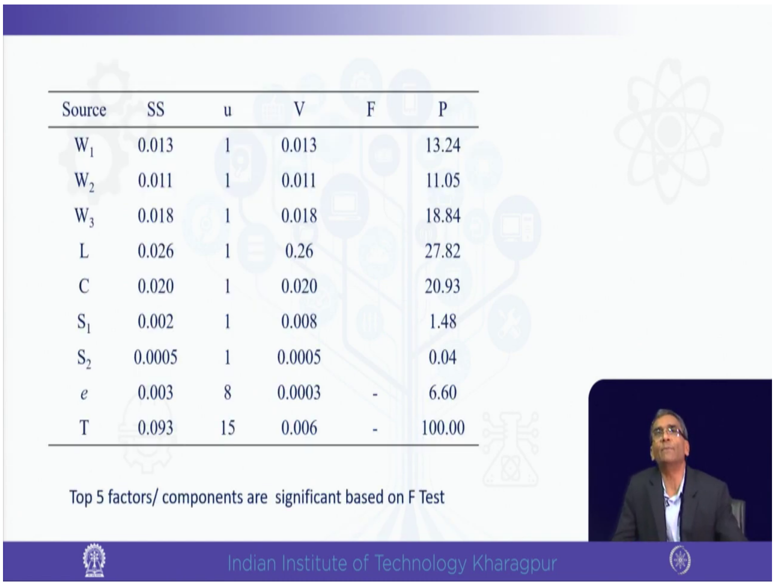

Source	SS	u	V	F	P
W_1	0.013	1	0.013		13.24
W_2	0.011	1	0.011		11.05
W_3	0.018	1	0.018		18.84
L	0.026	1	0.26		27.82
C	0.020	1	0.020		20.93
S_1	0.002	1	0.008		1.48
S_2	0.0005	1	0.0005		0.04
e	0.003	8	0.0003	-	6.60
T	0.093	15	0.006	-	100.00

So, what happens? We do the exact calculation as we did earlier same types of calculation and we recalculate these values based on the modified dimension of the lever and this casing by changing physically. And now we are finding from the result what is the outcome.

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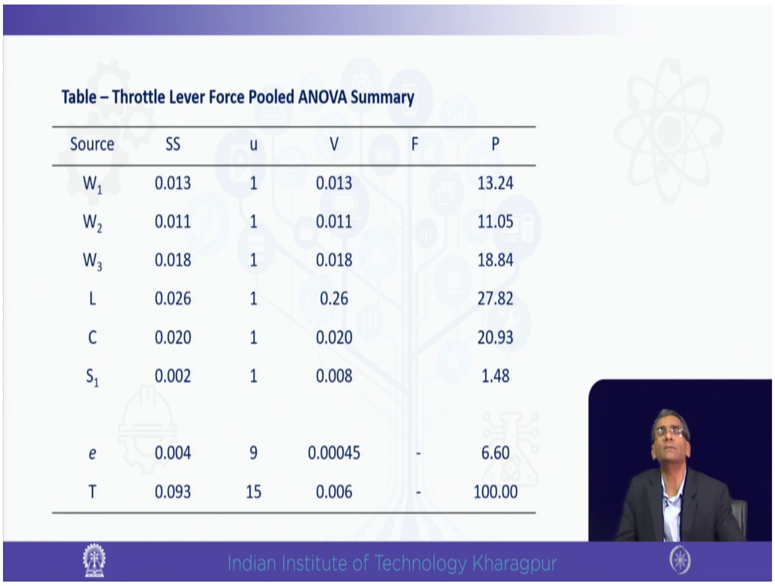

Table – Throttle Lever Force Pooled ANOVA Summary

Source	SS	u	V	F	P
W_1	0.013	1	0.013		13.24
W_2	0.011	1	0.011		11.05
W_3	0.018	1	0.018		18.84
L	0.026	1	0.26		27.82
C	0.020	1	0.020		20.93
S_1	0.002	1	0.008		1.48
e	0.004	9	0.00045	-	6.60
T	0.093	15	0.006	-	100.00

So, here the 5 factors or components are significant based on F test and here we see exactly with the same calculation and by pooling again that you see that here the S 2 is minimal. So, S 2 is merged with the error. So, 1 plus 8 becomes 9 S 2 goes. So, rest all remains that washer 1, washer 2, washer 3 lever casing and spring 1. So, this is what it is. Now, so now, again so the percentage contribution etcetera recalculated which you see on the last column.

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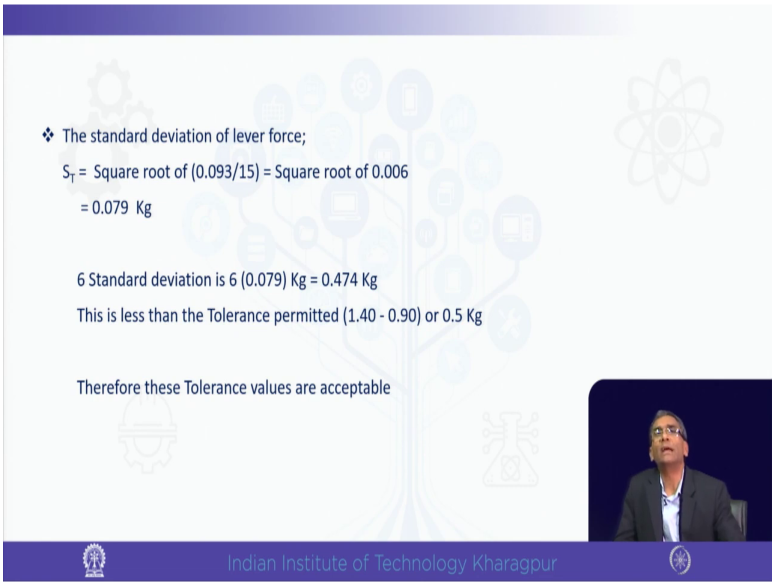

Now, what happens? This would now require us to find out the standard deviation which we have calculated square root of the variance which is 0.093 divided by 15 which we can see here total T sum of square is 0.093 by 15 and 600 deviation is therefore, 0.474 kg.

Now, we have to examine this is whether it is the it is meeting the specified tolerance range which is 0.5 kg 1.4 minus 0.9 now we see that it is meeting it 0.5 kg is the requirement and it is giving 0.474 kg therefore, this tolerance values are acceptable. So, here in through the steps you know how to set the tolerance for components. So, that outcome is influenced in a way that it meets their desired or target values.

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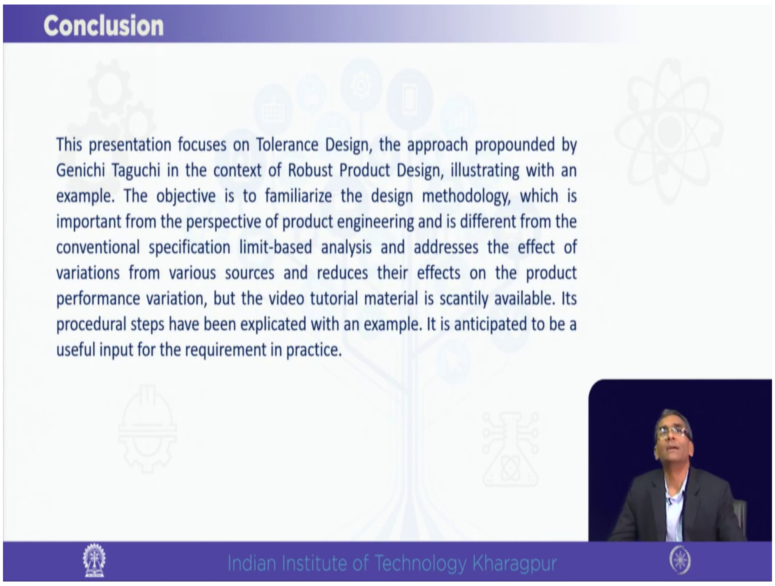

In conclusion I would like to point out that this tolerance design is has been explained with an example. The objective is to familiarize with the design methodology which is important from the perspective of product engineering and is different from the conventional specification limit based analysis and addresses the effect of variation from various sources and reduces their effects on the product performance variation.

But the video tutorial material is scantily available I repeat this procedural steps therefore, is in place that have been explicated with an example it is anticipated to be an useful input for the requirements in practice and for the students and for developing their product engineering skills particularly for complex products. Hope you will take interest and go through some of these statistical techniques easy to learn and you will certainly use it in certain applications of yours.

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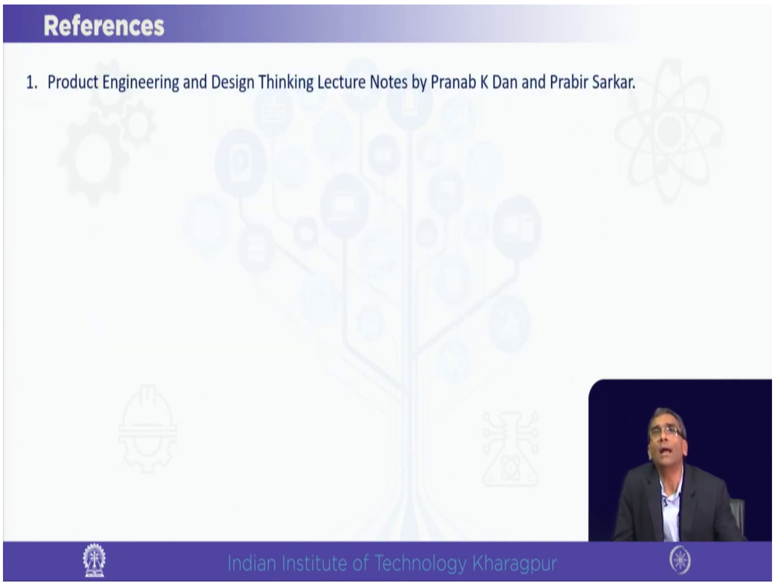

Thank you and before I close, I would like to mention the reference which is here and finally, I thank you for attending this lecture I am sure you would be it will help you and you would be using it in your work.

Thank you once again.