Design of Farm Machinery

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Lecture 12 : Design of tractor drawn cultivator

Hi everyone, this is Professor H. Raheman from IIT Kharagpur. I welcome you all to this SWAYAM NPTEL course on Design of Farm Machinery. Today is Lecture 12, where I will discuss the design of a tractor-drawn cultivator. The concepts which will be covered are the design of components of a cultivator, such as the design of a shank when it is fitted with a shovel or sweep, the design of a shank when it is fitted with a half sweep, the design of the frame, and ultimately the power requirement.

When I said the design of a tractor-drawn 9-tine cultivator, that means we have fixed the size of the cultivator to 9 tines. So, the next thing is to determine what information is required. We require information related to the type of soil, the speed of operation, the depth of operation, at what depth you are going to operate, and the type and size of the working element. Since this is a cultivator, the working element could be a shovel, a sweep, or a half sweep. So, suppose you are designing a shovel-type cultivator. The working elements are shovels, and the number of tines is fixed, which means we have already defined 9 tines. Then the question arises: what should be the size of the shovel? So, the normal size we take for the width of the shovel is 6 centimeters.

So, the width of the shovel is 6 centimeters—this is the width. Now, the working depth is 10 to 12 centimeters. So, we have taken 10 centimeters. So, to avoid overlap, we have taken delta t, which is equal to 2 centimeters.

Now, the spacing between two adjacent tines. So, that is denoted as t_0, $t_0 = (B_0+2a+\Delta t)$. 2a means maximum a × 2, I am talking about. If I substitute the values of B_0, Δt , and a, then I will get a spacing of 28 centimeters. So, t_0 I have got. The next thing is the spacing between front and back tines, that means, between rows. So, L - capital L. This is the distance that is equal to a tan 45 + 1, that means, a is the depth. So, the maximum depth we are taking as 10 centimeters, then spacing is t_s - t_s +10 centimeters, that way we got.

Sorry, t_s is your a tan 45 degrees, and small l is 30 centimeters. So, that's why we are getting a value of 40 centimeters. So, we fix the spacing between 2 adjacent tines. We fix the spacing between 2 rows. Then the next thing is, what should be the width? Width of cut or width of the cultivator? That will be equal to the number of tines into spacing between 2 adjacent tines. So, 9×28 that we were getting 2.52 meters. So, that will be the cutting width or width of the cultivator.

Then we have to design the cultivator for hard soil. In the beginning, I said the type of soil has to be defined. So, that will indicate what is the unit draft value. So, if it is hard soil because we are designing for the heaviest soil. So, that is why we are taking a maximum value of unit draft, which is 25 kN/m^2.

And the design resistance - soil resistance for which the shank has to be decided. So, for that, you have to take at least 3 to 5 times higher than the actual soil resistance you are encountering. So, to find out the soil resistance, we need to know what the cross-section of the furrow should be. So, it is a shovel-type cultivator. So, the cross-section of the furrow will be rectangular.

And per tine, I am talking about. So, this is the width, and this is the depth. So, the depth we have taken is 10 centimeters. So, that way, we can find out the draft, okay. So, what I have done here is for the total gang - total row, I have calculated. So, when it is 5 and 4 tines, that means 9 tines. 9 tines means in one frame there will be 5 tines, and in the other frame, there will be 4 tines. So, what I have done is I have taken the maximum number of tines. The frame which is having the maximum number of tines, I have taken that one. So, that way, $25 \times 0.06 \times 0.1 \times 3$. So, this 25 into 3 will give you the resistance. The unit draft value I have taken is 3 times, then multiplying with 0.10, that means 0.10 is the depth, this is the width, that is why you are getting that. So, what exactly I have done is: This is the tine. So, when you have taken 5 tines, this distance becomes $2t_0$.

So, 28×20 plus some spacing I have taken. So, that is why you are taking 0.06. So that way, we are getting per tine 450 Newton. Now, this is the horizontal component, which means draft. Now, for finding the vertical component, we need to know its value.

The load angle we have taken as 25 degrees, which means the load angle is this angle. Now, soil resistance is this one, and draft is this one. So, we have to now find out K_V. So, K_V will be equal to $K_H \tan(90 - \alpha)$. So that way we put. Per tine, we are getting a value of 965 Newton. So, the horizontal component, which is draft, we have calculated, and the vertical component we have calculated.

Next is how to utilize these forces to find out the dimensions of the shank. So, if you look at the figure here, the draft force is acting. Assuming that it is acting at the tip of the working element, then we need to know: What is the clearance between the tip of the working element and just below the frame? So, this is the lower portion of the frame. So, this height which is denoted here as H_1+a. a is the depth - this is your depth, and this is H_1, which is the clearance.

So, H_1 + a, if you know, you can find out the action of force. Action of force means the draft is giving you a bending moment. Since the working element is a shovel, then what will happen - it is a symmetrical tool. So, the draft force is going to create a bending moment. So, we are interested in finding out the bending moment. So, depth is known, and H_1, the clearance, is taken as 250 millimeters. This I have already discussed in our previous class, where I discussed the design aspects of a cultivator.

And then ΔH is 50 millimeters. This ΔH has no role because this has to be inserted into the frame. So, this is not going to act as a moment arm. So, only the first two components are responsible. So, the height of the shank will be 350; I have neglected the ΔH value.

Then, the shovel is symmetrical about the vertical axis. So, the bending moment acting on the shank will be equal to K_H, which is equal to K_{OBL} now into H_1+a. So, that way, you are getting this 337.76, because we are designing for a single shank. So, we are considering only one tine. Now, the next thing is: what is the stress coming on the shank because of the bending moment? Stress due to bending is a simple bending case.

So, what will happen here, the stress due to bending $\sigma = M_b/Z$. Section modulus means moment of inertia by y, where y is the distance of the extreme fiber from the neutral axis. So, for a shank, we have to first decide what the shape of the shank should be, then only you can find out what is the value of z. So, we have to assume a design stress for mild steel. So, for example, mild steel means the maximum allowable stress is 150 Mega Pascal. Taking a factor of safety as 3, we try to calculate what is the design stress? and that way it is coming to 50 Mega Pascal.

So, we assign the value of sigma as 50 Mega Pascal, and then we try to find out these dimensions, the dimensions of the shank. Assuming that the shank has a rectangular cross-section, that means it has a width h and a thickness b. This is h. Sorry, this is h. Now, this is clearance. So, the section modulus for this rectangular cross-section will be equal to $\frac{bh^2}{6}$, that means moment of inertia $bh^3/12$, then y will be equal to h/2. So, that way we are getting the Z value - section modulus as $\frac{bh^2}{6}$.

So, now assuming a ratio between b and h, that means the width to thickness ratio. So, the h by b ratio is taken as 3 is to 1. So, the z value, if I substitute for h in terms of b, then I am getting the section modulus as equal to $1.5b^3$. Now, substituting this value in this equation. So, I am getting this. So, from where I can solve to find out b, the thickness. So, that way I am getting 1.65 centimeters. And so, the width will be 3 times the value of b. So, that is why I am getting 4.95 centimeters. Now, this will be the case when there will be no - the working element is symmetrical, but when the working element is not symmetrical, then, for example, the shank is provided with a half sweep, then things will be a little different. Different in the sense the shank will now be subjected to both bending and torsion. So, that will be creating bending as well as torsion.

So, K_H into H_1 + a, which is the distance from the point where it is fastened - the shank is fastened to the beam, then K_H into H_1 + a, that will give you the bending moment. Now, K_H, if you look at the front view, then this resultant K_H, which is passing half the working width of the half sweep. So, if the full sweep working width is W, then half will be W/2, and the soil reaction force, which is the draft force K_H, will create a torsional effect about the shank. So, this is a half sweep of width 10 centimeters, and then, since it is not symmetrical about the vertical axis, there will be bending, and there will be torsion. So, we have to calculate now what is the bending moment and what is the torsional moment. Assuming that the width is 10 centimeters and again the cross-section of the furrow to be rectangular. So, we try to find out the torsional moment. So, design draft on half sweep into W/2, that will give you the torsional moment. So, design draft we have calculated as $25 \times 0.10 \times 0.10 \times 3$. So, 0.10 is the width. So, 0.10, 0.10 is the depth here, then 3 is the factor of safety for the soil resistance, which is the draft force we have taken, then half width 0.1/2. So, that way you are getting a torsional moment of 37.5 Newton meters. Now, the bending moment will be equal to $K_{OBL} \times (H_1+a)$, where, H_1+a we have already determined as 350 millimeters. So, now, K_{OBL} is nothing but draft into 3 times. So, that way you will get a value of 262.5 Newton meters. Now, when a material is subjected to both bending and torsion, the equation will be half the stress developed due to bending, due to torsion - the combined effect that will be equal to $\frac{1}{2}\sqrt{(\sigma_b)^2 + 4(\tau_s)^2}$. So, for finding this out, we need to know how to calculate the torsional moment. For this torsional moment, you have calculated. Then, corresponding to the torsional moment, what will be the stress developed? So, that will be equal to the torsional moment multiplied by y divided by the polar moment of inertia. So, this is the polar moment of inertia for a rectangular section. Since I have already assumed that the shank is of a rectangular cross-section with width h and thickness b. So, b h into b squared plus h squared by 12 becomes your polar moment of inertia, and y by 2 is nothing but h by 2.

Now, b is the thickness, and h is the width of the shank. So, we try to calculate the value of the shear stress that is developed. Now, again, we try to express it in terms of either b or h. So, we have to assume a ratio of h/b, which is taken as 3 to 1. So, the torsional stress, τ_s = TM×0.6/b^3.

Next is the stress due to bending. So, you have already done this $\frac{6 \times BM}{bh^2}$. So, again h by b ratio you have taken as 3 is to 1. So, that way you are getting $2 \times BM/(3 \times b^3)$. So, the total expression for stress due to torsion and stress due to bending has been expressed in terms of b, the bending moment, as well as the torsional moment. So, now, substituting this in this equation and taking the $\boldsymbol{\tau_{max}}$ value, design shear stress value, as 50 Mega Pascal and considering both shock and fatigue factor as 1.5 for both the cases, that means, for bending as well as torsional moments, then this will be the expression for shear stress developed. Now, substituting these values, finally, you got the b value of 1.39 centimeters and since h is 3 times b. So, we will get a value of 4.18 centimeters.

So, this is about the design of the shank when it is fitted with non-symmetrical working elements like your half sweep.

Next is, after deciding the shank dimensions, the next thing is what should be the dimension of the frame on which the shanks are to be fitted. So, when you are fitting the shanks into a frame, you have to take the maximum number of tines the frame is having or carrying. So, 1, 2, 3, 4, 5 out of 9 tines, 5 tines are fitted. So, I have taken that frame.

Now, let us find out what are the forces which are acting. So, at each tip of the tine, there will be a vertical force acting, and in the case of the cultivator, the vertical force is always acting downward. So, I have given the direction of K_V downward. Now, the weight - the weight of the implement. So, the weight of the implement, if you take as W, then half of that is taken as W_g, which is acting on one frame.

Now, knowing the forces which are acting, the next thing is how to find out the support reactions R_1 and R_2. So, R_1 and R_2 will be nothing but the summation of the vertical forces acting divided by 2. So, the total vertical forces - soil reaction forces is 5 K_V, and this is W_1 ×5/9, which means what I have done is: the total weight is - the total weight of the implement is W1. So, it has 9 tines. So, I have divided by 9, and then, since 5 tines are fixed to the frame, I multiplied by 5. So, that way, it is more or less giving you the accurate result of how much weight is coming on the front gang or the rear gang.

So, that way, R_1 and R_2 become 3093.82 Newton. The next thing is how these forces are going to act on the frame and what are the resultant effects. So, the vertical force is going to give you the bending moment. So, if you draw the central line here, this will be the central line. Now, taking moments about the central line.

So, we are getting the bending moment will be equal to R_1 into this plus this plus this, that means $2t_0$ plus $2t_0$ plus t_0 by 4, then K_V. So, this is acting downwards of minus K_V into 4t0, then again K_V into $2t_0$ minus $2t_0$ plus this distance W_g by 2, half of the weight is acting on this side, half of the weight is acting on this side. So, $W_g/2$ $(2t_0 + t_0/4)$. OK. So, that means, the total distance divided by 2.

So, that is $W_1/2$ that I have taken. So, finally, this is the expression since t_0 we have already calculated. So, I have not multiplied each term. So, finally, here I have multiplied to find out the value of the bending moment due to the vertical force, where t_0 value is taken as 28 centimeters. The next thing is the torsional moment.

If you look at this diagram, the other way if you look at the horizontal forces will act at these points, so that will try to create a torsional effect - a torsional effect on the beam. So, we have to find out what the torsional moment acting is. So, the torsional moment will be equal to again what is this horizontal component of soil reaction which is nothing but your draft, then what is the clearance. So, that way this will be H_1 you have taken 25 depth is 10. So, that way the clearance becomes 0.35 meters.

And then 450 is for one tine; there are 5 tines. So, when I multiply that, it gives you this much Newton meter as the torsional moment. Now, the stress due to torsion is again calculated assuming the cross-section of the frame to be a rectangular. So, this is h, this is b. Now, if I substitute here, so, torsional moment × y/2 and then this is your polar moment of inertia. So, that way we are getting the expression for stress due to torsion and stress due to bending you have calculated.

Then you have to find out - assuming the ratio of h/b as 3/1 - we calculated the stress due to torsion in terms of b cube. And stress due to bending in terms of b cube and bending moment, and this is the governing equation. We are considering the maximum shear stress theory. So, the allowable or the design stress due to shear will be equal to $\tau_{max} = \frac{1}{2}\sqrt{(\sigma_b)^2 + 4(\tau_s)^2}$. So, that way we are getting the shock and fatigue factor, which we are also taking as 1.5, and that is for both bending as well as torsion. Then, the design shear stress we have taken with a factor of safety of 3.

So, that way, tau max becomes 50 Mega Pascal. Now, when I substitute here in this equation, I got the expression. So, from here, I can see that b cube is this much. So, b comes to be 0.0278 meter, which means 2.785 centimeters. So, h will be 3 times that. This is 2.785. So, 8.356. So, roughly, you can take 8.36 centimeters. So, this will be the value for the size of the frame.

Then comes the power requirement for operating the cultivator. So, when I said power requirement, because we have not designed for any tractor, what we have done is we have designed a 9-tine cultivator. Then, you will try to find out how much power will be required to pull it. So, that will be the minimum tractor power requirement.

So, for that, we need to know how to calculate the power requirements. So, the power which is required will be the drawbar power because the working elements are not powered. So, all the power requirements will be based on drawbar power. So, the drawbar power requirement for operating the cultivator will be the drawbar power required for operating the implement and the drawbar power required for moving the tractor and implement forward. So, for calculating the drawbar power for operating the implement, we need to know the forward speed.

So, we have already determined that the forward speed is 4 km/h. So, that way, it is giving you 1.11 m/s. Then, the power - drawbar power required for operating the implement will be draft multiplied by forward speed. So, the draft is 450 Newton per single tine. So, you have to pull the entire implement, which is why it is multiplied by 9, 9 implements, and this is the forward speed. So, we are getting a power requirement of 4.5 kilowatts.

Now, assuming the weight of the tractor to be around 2000, a little above 2000 kg. So, we have taken 2000 kg and the weight of the total cultivator as 250 kg. So, then the total weight of the tractor and cultivator comes down to 2250 kg. Now, assuming the rolling resistance to be 8 per cent of the total weight. So, that way, the force required, that means the rolling resistance, will be equal to 8×2250 kg.

So, that way you are getting 180 kg. So, this is coming from $(8/100)\times2250$. Now, the forward speed is 1.1 m/s. Now, the power requirement for propelling will be 180 kg. We have converted it into - it was in kg force. So, multiply by 9.81 to find out in Newton, the Newton meter per second, that way you are getting this much watt, which is equal to 1.96 kilowatt.

So, now, the total drawbar power requirement will be the summation of these two. Summation of the drawbar power for operating the implement and the drawbar power required for moving the implement and tractor forward. So, that way you are getting a power requirement of 6.46 kilowatt. Now, taking 20 per cent as the power reserve. So, the power available for operating the cultivator we have calculated.

So, the power available should be just divided by 0.8. That way, this is the power that should be available at the drawbar. Now, if you want to find out the engine power, then we have to assume the tractive efficiency and you have to assume the transmission efficiency. So, when we divide those two efficiencies with this drawbar power requirement, then we will find out what is the engine power required. So, I have divided 8.075 with this efficiency and this efficiency, that is our transmission efficiency and tractor efficiency. So, that way we are getting 16.412 kilowatt.

So, the minimum power requirement is 16.412 kilowatt. So, a 16-kilowatt tractor can roughly be said to easily pull that 9-tine cultivator. This is how you have to find out the dimensions of different components of the cultivator, and then from there, knowing the power requirement, you can find out the total power of the tractor which will be responsible or which can be selected for pulling the implement. So, these are some of the references which are used for calculation purposes, and then in summary, you can say we have covered the design of components of a tractor-drawn cultivator. Then, what is the minimum size of a tractor required to operate a cultivator? Those things are discussed.

Thank you.