Design of Farm Machinery

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Lecture 11 : Forces and moments acting on the shank and frame of a cultivator

Hello everyone, this is Professor H. Raheman. I welcome you all to this SWAYAM NPTEL course on the design of farm machinery. This is Lecture 11, where I will discuss the forces and moments acting on the shank and frame of a cultivator. The concepts covered here will include the forces and moments acting on the cultivator shank and frame, followed by some numericals related to cutting width, volume of soil handled, and power requirement of a cultivator. We need to know what forces are acting on the shank, as they will affect the design of the shank and the frame.

So, let us now see what the soil forces or the resistance acting are. There will be a soil reaction, and the soil reaction will have two components. The soil reaction will depend on the type of working elements attached to the shank. Suppose the working element is a symmetric working element; symmetric means the shovel is a symmetric working element, and a full sweep is a symmetric working implement. That is why I have written a shovel or sweep.

For design calculations, the resistance we take is 3 to 5 times more than the actual soil resistance acting on the working element. To find out the soil resistance acting on one tooth, we need to know the total working width and the draft value. Draft value means unit draft value or specific draft value. In this equation, we can see draft $K_x = a\frac{B_k}{n}p_K$. B_k is nothing but the working width; if there are n times, then n into spacing between two adjacent tines will give you B_k, neglecting the overlap. Now, n is the number of tines. So, when I divided B_k by n, that will give you the width covered by each tine, and p_k is the unit draft or specific soil resistance. This is possible when the cross-section of the furrow is rectangular. So, we assume that the cross-section made by the cultivator tine or tooth is a rectangular furrow section, and the width is equal to B_k/n, and the depth is a. So, then a $\times$ B_k/n will give you the area: the cross-section of the furrow multiplied by the specific resistance. Specific resistance is nothing but draft for unit cross-sectional area; that value has to be available for different soil conditions. So, I have listed some of the values you can see: light soil, medium soil, heavy soil, and very heavy soil. The values are given in kilo Newton per meter square. It starts from 12 to 20 and ends at 25, which means, for very heavy soil, it is 25. Heavy soil means clay soil or compacted clay soil, like that. So, once you know this, you can find out how much is the draft force acting.

The other way of calculating the soil reaction is: you take the help of the ASABE equation. Here, the draft value is given as $D = F_i[A + B\,(S) + C\,(S^2)]T \times W$. W depends on whether you are interested in finding out for each individual tine or for the total working width. Now, to utilize this ASABE equation, we need to know the values of A, B, and C, and what will be the working width, and in which soil you are going to operate. So, I have collected some information, like the values of A, B, and C for a field cultivator.

The values of A, B, and C you can see are 32, 1.9, and 0. For a row crop cultivator, the value of A is 260, B is 13, and C is 0. And if you look at the equation - the ASABE equation - then you have to select what type of soil you are going to work on. That means the value of i could be 1, it could be 2, or it could be 3. So, depending on the values, we can find out what is the value of Fi, and knowing this, we can directly calculate what is the draft value.

So, there are two possibilities; the first possibility is that the unit draft value should be available. Or, if the unit draft value is not available for a particular soil, then we go for utilizing the ASABE equation. If you look at the variation, the variation is between 15 to 25 percent. In spite of these variations, we have to take this value because we do not have any other way to design. So, we need to know what the draft value is?

Next is, when the shank is symmetrical, how this draft value is going to affect that, we need to know. So, the shank is fitted to the frame, and the soil resistance is acting at the tip. I have taken it at the tip, but before, I discussed that it is acting at a height of 0.2a. So, either way, you can take it at the tip or you can take it at a height of 0.2a. The only difference is, if you take it at the tip, then you are utilizing a higher H value. If you are taking it at 0.2a, then you are reducing the H value by 0.2a. Now, this force which is acting - the draft force at the tip - is going to create a bending moment of the shank, okay.

So, if the shank cross-section is a rectangular one with width h and thickness b, then the stress due to bending will be equal to $\frac{M_{zg}}{z}$; z means nothing but the section modulus. So, which I have denoted as: M is the bending moment into y if I simplify this one by the moment of inertia. So, the moment of inertia of a rectangular section is $bh^3/12$ about the x-x axis; then y will be equal to h/2. So, if I substitute here, then I can find out - then I try to find out M. M will be equal to K_{obl}; K_{obl} is 3 to 5 times more than the draft value. So, draft value whatever you have taken, just take and multiply it by 3 to 5. So, for the factor of safety, we are designing for a higher value. Into H_1 + a means, this distance - clearance plus depth. So, that will give you the bending moment. So, this is giving you the bending moment.

Now, I y by y. y is h by 2. So, bending moment M. So, $\sigma = \frac{M}{\frac{b\,h^2}{6}}$. So, if you can calculate M, but there are two unknowns now: b and h. So, we have to fix a ratio between b and h, so that we can find out by taking the value of sigma. This is the case when the working element is symmetrical. If the working element is not symmetrical, like half sweep or a knife, then the shank is subjected to both bending as well as torsion.

So, bending force will be equal to the same draft into clearance H_1 + a, whereas, the torsional moment will be equal to TM = K_{obl}×(cutting width of half sweep/2),. If half sweep is this, so half. Assuming that the resultant soil reaction is acting here. So, this will try to twist this shank. So, this is your half sweep W/2, sorry W. So, this is W/2. So, K_{obl}×(cutting width of half sweep/2), this is your total cutting width. So, that will give you the torsional moment.

So, now, you know the bending moment, and you know the torsional moment. Then you try to calculate utilizing the maximum shear stress theory, and we try to find out by taking the help of this equation. This is again the shank with a rectangular section of width h and thickness b. So, that will be - the stress due to torsion will be equal to TM, torsional moment × h/2 divided by the polar moment of inertia. The denominator is the polar moment of inertia about the x-x and y-y axis. So, that way, again there will be two unknowns, b and h. So, we have to fix a ratio, and the ratio is usually taken as 3:1.

Then K_b and K_t values you have to take, meaning these are shock and fatigue factors for bending moment and torsional moment. So, that we can take as 1.5 to 2 values in between, or you can take 1.5. Then, assuming a maximum stress value depending on the carbon content of the material which you select, we can fix the shear stress value. So, if you know the allowable shear stress value, substitute it and then find out what will be the value of b and h. That means, stress will be - allowable stress will be equal to $\frac{1}{2}\sqrt{{\sigma_b}^2 + 4 \times {\tau_f}^2}$. So, τ_f you calculate from here. There will be unknowns b and h. We express them in terms of h. Similarly, in σ_b also we have and there are no unknowns here, there will be b h by 12. So, that will be there. So, finally, you solve this equation. This value you can take considering the factor of safety as 50 Mega Pascal. So, then you solve this to find out what will be the dimensions of the shank. So, the only difference is in a half sweep, the shank is subjected to both bending and torsion, whereas in a full sweep or a shovel type, where the working elements are symmetrical, the shank is subjected to only bending. That is the difference. So, the calculation for a symmetrical tool or element will be - the working element is much easier than the calculation for the non-symmetrical working element like a half sweep.

Then comes the forces acting on the frame, forces, and moments. So, if you look at this diagram, there will be - at each tip of this working element, I have indicated two forces. Because the soil reaction will have two components, one is the horizontal component, which is the draft, and the other one is the vertical component, which is K_v. And the vertical component is always acting downward, unlike your disk plough or disk harrow, where it is always acting upward. So, K_v is acting downward. So, here the main thing is, which frame has to be designed. There are two frames because there are two groups of tines.

So, we have to first find out which frame, the front frame or the backside frame - or the rear side frame, is carrying more tines. So, the frame which is carrying more tines has to be taken for design, and the same dimension is to be followed for the other frame. So, if you look at this figure now, you can see there will be 5 tines in the front. This is a 9-tine cultivator, 5 in the front and 4 in the back, or 4 in the front and 5 in the back; both arrangements are possible. So, when you take 5 in the front, I will design the first part, the front gang. There will be 5 vertical forces and 5 horizontal forces acting, and the distance between 2 adjacent tines in the front row will be twice the spacing between 2 adjacent tines. Adjacent tines mean these 2 are adjacent - one in the front and one in the back. But when you consider only one frame, the distance should be just double the value you have considered.

Now, there will be 5 - 1, 2, 3, 4, 5. The support is at the end. So, R_1, support reaction will be equal to, R_1 is equal to R_2 is equal to $5K_V$. $5K_V$ they are acting - summation of the vertical force and the weight of the frame, ok. That way, W_1 is the weight for each tine. So, weight into 5 by 9 means, the total weight, if you know, divided by 9 will give the weight of each tine multiplied by 5, which will give you the weight of the front gang. So, the summation of these divided by 2 will give you the reaction force R_1 and R_2.

Now, the frame is subjected to both bending and torsion. Bending is due to this vertical force, and torsion is due to the horizontal force, which is your draft. So, bending is due to R_1 and W_g and K_V, and torsion is due to K_H. Using the maximum stress theory again, we will try to calculate the dimensions, assuming the cross-section to be either rectangular or solid square. Here, weight is not a factor because K_V is acting downward. So, we do not have to add extra mass, as in the case of a disk harrow, where we are interested in adding more mass because K_V is acting upward. So, we try to set the K_V value downward. To do that, we add some extra mass on top of the frame. But here, that problem does not exist because K_V is already acting downward. So, you can keep the mass as minimal as possible so that rolling resistance is reduced. Using this maximum stress theory and taking the allowable shear stress as 50 Mega Pascal, since the frame is made of mild steel. So, you can calculate the shear stress due to torsional moment, the stress developed due to bending moment, and then, using this equation, we can find out the allowable stress considering the stress induced by the cross-section.

As I said, the cross-section can be square or rectangular; both are possible. Now, I will solve some problems to provide more clarity, in the sense that you will know how to calculate the cutting width, how much volume is handled, how to calculate the area covered, or how to calculate the power required to propel the implement forward.

The problem is: the total distance between the left most tine and the right most tine of a 9-tine cultivator is 160 centimeters. If the cultivator is operated at 3 km/h with a field efficiency of 78 per cent, calculate the actual field capacity. So, what is given is the distance between the left most tine and the right most tine. So, what does it mean? If you look at this figure, the distance between this one and this one is given. So, that is equal to: if it is a 9 tine, then this distance is equal to 8 times the spacing between 2 adjacent tines. If you look at the figure, it will give more clarity now. So, you have 2 spacings here: twice t_0, twice t_0, twice t_0, twice t_0. That means, 1, 2, 3, 4. There will be 5 tines in the front. So, there will be 4 spacings, and that spacing is equal to 2 times t_0. t_0 is the spacing between 2 adjacent tines. That means, this row, this row, this is t0. So, 8 spacings, 8 into t_0, is equal to 160. Now, the working width will be how much? t_0 will be 20 centimeters, and the working width will be equal to 9 times t_0. So, 20 × 9, that way 1.8 meters.

Now, what is asked is field capacity? So, first, we try to calculate the theoretical field capacity, then we calculate the actual field capacity. So, the theoretical field capacity will be equal to the cutting width multiplied by the forward speed. So, the forward speed is given as 3 km/h. So, 1.8 × 30/36, that will give you the area covered per second.

If you do not want to find out per second, if you want to find out per hour, then do not divide by 36. Just simply make it 3000 meters. So, 1.8 meters, 3000 meters, the answer will be in m^2/h, okay. Now, since field efficiency is given, so, actual field capacity will be equal to field efficiency × theoretical field capacity. So, theoretical capacity has been calculated, multiply with field efficiency 0.78. So, that will give you actual field capacity, which comes around 4212 m^2/h.

This one is 5400. This one, actual field capacity becomes 4212, m^2 - m^2/h. So, you have to be very careful while deciding this spacing. In the front row, if you are taking spacing, that is twice the spacing between two adjacent tines, which is denoted as t_0.

Now, find the volume of soil handled - another problem dealing with. Find the volume of soil handled per unit time, when a tractor-drawn 11 into 30 centimeter shovel-type cultivator is operated in sandy loam soil at a depth of 10 centimeters and at a forward speed of 4 km/h. So, what is given is 11×30, that means, the working width will be straightway it will be 11 into 30. So, 330 centimeters straightway, you can calculate the width. Then what is given is depth, depth is given as 10 centimeters and forward speed is given as 4 km/h. So, volume of soil handled will be equal to t × a × speed. So, you take care of the units. So, t is in centimeters.

So, let me convert it to meters. So, 3.3 meters. As it is in centimeter, so, 10 by 100. S is in km/h. So, I will make it m/h. So, if I multiply this, that will give you volume in m^3 and time is per hour.

So, that way, it comes around 0.367 m^3/s or 1320 m^3/h. So, to calculate the volume of soil handled, we need to know the working width, and you should know how to calculate working width, and then depth is given, forward speed is given, just multiply these three units and get the volume of soil handled.

So, the third question is, if the unit draft of a tractor-drawn 9 by 25 centimeter shovel-type cultivator when operated in sandy loam soil at a depth of 10 centimeters is 25 kN/m^2, find the total draft requirement of the cultivator. If the total weight of the tractor and cultivator is 2500 kg, assuming the rolling resistance of the tractor and cultivator as 10 per cent of its total weight, find out the total power requirement to carry out tillage, when the cultivator is to be operated at a forward speed of 4 km/h. So, there are a number of things to be calculated; first is to calculate the draft requirement, and the second thing is to calculate the total power requirement to carry out tillage.

So, first, to calculate the total draft requirement, you should know - either you can utilize the ASABE equation, or you can utilize the unit draft values multiplied by the cross-section of the furrow. So, now, in this question, since the unit draft is given, we first assume that the furrow section is rectangular. And the width of the furrow is not exactly the furrow; the width of the cut will be equal to 9 × 25, and then the depth is 10 centimeters, and the unit draft is given. So, unit draft multiplied by depth multiplied by width. So, that will give you the draft value, okay. So, this much power, and if you know the draft, this much force should come from the tractor.

In addition to that, there will be a rolling resistance, and the rolling resistance value is nothing but the resistance to move forward. So, you need to move the tractor as well as the implement. So, the total weight is given as 2500 kg, and the data given is the rolling resistance of the tractor and cultivator is 10 per cent of the total weight. So, the rolling resistance will be equal to 10 per cent of 2500, ok, so 250 kg. So, we have the draft, and we have the rolling resistance. Now, they are to be multiplied with forward speed to find out what is the power required to pull the implement, what is the power required to move the implement forward, as well as the tractor.

So, draft × speed plus rolling resistance × speed. This is the power required to move the tractor and implement forward. This is the power required to move the implement - to pull the implement, the summation will give you the total power requirement, ok. So, the detailed solution I can give you. So, first, I calculated the draft value, which comes around 0.625 Newton. Then comes your total draft experienced - number of tines × draft experienced by each tine. So, here I have taken only 0.25, that is why it is giving you per tine. So, while I discussed, I calculated 9 × 25 directly, that means it will give the total draft value.

Then comes your - we do not have to multiply with the number of tines, what I did in the beginning. Then, total draft × forward speed that will give the power requirement to pull the implement. Then, the power required to overcome rolling resistance is 10 per cent of the total weight into forward speed. So, 10 per cent of total weight is 0.1 × 2500, converted into Newton to find out in Watt. Total power required for operating the cultivator at a forward speed of 4 km/h will be power required to pull the cultivator and power required to overcome the rolling resistance. So, that way 6.25 is for pulling and 2.725 kilowatts is for rolling - overcoming the rolling resistance. So, the summation will give you 8.975 kilowatts.

So, this is all about what we discussed with these references. And the conclusion is: the forces and moments which are acting on the cultivator shank and frame are discussed, along with some numericals for computing cutting width, volume of soil handled, and power requirement of a tractor-drawn cultivator. That is all.

Thank you.