Design of Farm Machinery

Prof. Hifjur Raheman
Agricultural and Food Engineering Department
Indian Institute of Technology Kharagpur
Week – 03

Lecture – 15 : Design of components of a rotavator

Hi everyone, this is Professor H. Raheman. I welcome you all to this SWAYAM NPTEL course on Design of Farm Machinery. This is lecture 15, where I will discuss the design of components of a rotavator. The concepts which will be covered are the design of components of a rotavator, including the blade, the shaft, how these blades are arranged, and the power requirement for operating a rotavator. So, I will start with a problem. The problem is: when a tractor PTO-driven rotary cultivator with L-type blades of rotor radius 25 centimeters is operated at a forward speed of 3.5 kilometers per hour and at a depth of 12 centimeters, the tilling pitch obtained is 12.5 centimeters.

If the mean torque acting at the rotary shaft is 213 kg·meter, with a coefficient of soil-specific resistance C0 as 2.5, specific soil resistance as 0.2, and coefficient of dynamic soil resistance as 450 $kg \cdot s^2/m^4$. Then, the number of blades working in one plane on each disk is 2, the width of each blade is 14.5 centimeters, and the tractor PTO speed is 540 rpm. Calculate the total working width and the number of working sets of the rotavator. So, the question is a little lengthy because we need some more information before we can calculate this. So, the basic thing is: what is the peripheral speed? That has to be computed. Peripheral speed computation can be done from the tilling pitch.

So, the tilling pitch is given as 12.5 centimeters, and the forward speed is given. The z value is given as 2, but n is not given. So, n has to be found out. Only the PTO speed is given, but the rotor speed is not given. So, from here, we can find out what will be the value of n. So, n comes around 6.11 meters per second. Because the rotor radius is given. So, that is why directly we are getting n as 233.33. Then the peripheral speed we have computed comes around 6.11 meters per second.

Now, specific work is equal to $A_0 + A_B$. Static specific work, dynamic specific work. The static specific work is dependent on two factors, C_0 and k_0. The value of C_0 is given as 2.5, and k_0 is the specific soil resistance, which is given as 0.2 kg per centimeter square. So, we can compute A_0 from this. Then, that way, A_0 comes to 5000 kg per meter square. Then, the dynamic specific work $A_B = \alpha_u u^2$. So, u we have calculated. Alpha u value is given. Coefficient of dynamic soil resistance, 450 kg-s^2/m^4. So, you can compute A_B that way. It gives 16799.45 kg/m^2. So, we got the value of A_0, and we got the value of A_B. So, then we compute the total specific work, which is nothing but the summation of these two. That way, it comes to 21799.45 kg/m^2. The next thing is, if you put it in the specific work equation, tilling pitch is given. The specific work equation is: $\frac{2\pi M}{Volume\ of\ soil\ handled} = \frac{2\pi \times M}{abl(iZ)}$. This is in the concurrent mode. So, that is why I have not taken the pushing force component, only $\frac{2\pi \times M}{abl(iZ)}$. Here, b is the blade width. So, that is why I have multiplied i and Z. Z is the total number of blades in one set. l is the tilling pitch. So, in this equation, a is given, b is also given, and tilling pitch you have calculated. Tilling pitch is also given. Z is given; only i is not given. So, we have calculated A, and torque is given - torque M is given. So, if you substitute here, these are the values given now. You substitute in the equation. So, i Z will be equal to 28. That means the total number of blades will be equal to 28.

Now, the question arises: how to arrange these blades? So, since I said – in the question, it is given that 2 blades will be working in the same plane, that means in each set there will be 4 blades. So, there will be 7 such units. But in a rotavator, it is usually arranged like this: the last 2 ones throw soil inwards, which means they have only one set of blades, and the rest of the units will have blades in both directions. So, these 28 blades will be arranged in 7 sets. The last 2 sets will only carry 2 blades, and the rest 5 – 1, 2, 3, 4, 5, 6, 6 plus 2. So, that way you are getting 6. So, these are 4 blades: 6 into 4, 24, and 2 blades at the end. So, that way you are getting 28 blades. So, the cutting width will be, so, the angular interval will be 360 divided by 28. So, this is the angular distance between 2 blades that has to be maintained. Then, the total number of blades is 28, and they have to be arranged in 6 disks and 2 on the side, so 8 disks.

And you have to provide some gap between 2 such units so that the 2 blades should not cause any clogging. That gap I have taken as 1cm. So, the total length will be equal to – 14.5 is your width. So, each set will have a width of 14.5, 14.5 that way 29 centimeters. Then, 6 times that one plus these 2 – 14.5 on this side, 14.5 on this side plus 7 gaps – 7 centimeters. That way, we were getting a cutting width of 2.1 meters. So, this is how the blades are to be arranged in the case of a rotavator. The next thing is the design – the design of the shaft of the rotavator.

So, the shaft of the rotavator is subjected to both bending as well as torsion. Bending is due to the vertical force, which is K_y, and the weight of the implement. And K_x, the horizontal component, will create torsion. So, let us now see how to find out this horizontal component. So, we have the expression for the horizontal component and the vertical component. So, the vertical component K_y K cos ($\alpha+\psi-\Delta\delta$), and K, for design purposes, we can directly take as the peripheral force, that means, torque divided by R. Though I have written here M by R', because R' is changing. So, you can directly take the K value as the peripheral force. Then, the only thing is cos ($\alpha+\psi-\Delta\delta$). The ψ value has to be taken as 10 to 15 degrees, and the $\Delta\delta$ value depends on the u/V ratio. The higher the u/V ratio, the lower will be the value. That means, these two components will be very minimal. So, since cutting starts from, say, in a concurrent mode, 20 degrees to 100 degrees. So, the cos value will be maximum there at 20 degrees.

So, we have to take around 20 degrees to get the peak vertical force. Similarly, for the horizontal force, it is the sin component. So, between 20 to 100, it will be 90 degrees. sin 90 will give you the maximum force. So, K_x you can directly take as K sin$\boldsymbol{\alpha}$. K sin 90 means K. K_x would be equal to K, since sin 90 is equal to 1. So, you can take it directly as the peripheral force.

The horizontal component will be maximum, which I want to discuss. Then, look at the arrangement of blades. This arrangement has been made for 48 blades, all of which are L-type. So, 48 blades mean one-fourth of the maximum number of blades, which means 12 blades maximum will be in contact with the soil at a particular instant of time. That means there will be 12 vertical forces acting. So, how to distribute these forces? There will be 1, 2, 3, 4, 5, 6, 7, 8, 9.

So, there are 9 sets. In 9 sets, there are 9 vertical forces plus 3 extra, which I have taken on either side of the center line and at the center. So, that is why I have indicated 2 K_v here, 2 K_v here, 2 K_v here, and the rest are providing K_v only. So, that becomes 6 + 3, 9 + 3, 12. So, 12 K_v. Now, what is the weight coming?

If the total weight is W, say W/2 is coming—W' here is indicated. So, W'/2 is acting on this side, W'/2 is acting on this side, and the spacing is indicated as W_d. The spacing between two adjacent sets is W_d, and the support is given on either side with the width given as $W_d/2$. So, the reaction force R_1 and R_2, which is coming at the support, will be equal to the total vertical force acting downward minus the total vertical force acting upward, divided by 2. So, the total weight of the rotavator is W', and the vertical forces, K_v, acting on the blades equal one-fourth of the total number of blades. So, that way it is 12, then divided by 2. So, that way this is the expression for calculating the support reactions of the support. Next thing is, what is the bending moment? Bending moment acting on the shaft due to vertical force. So, now, you take the bending moment about the center line.

So, R_1 into this distance, that means, W_d, W_d, W_d, W_d, 4 times plus 0.25. So, R_1 into this. This is positive. and then K_v, I have expressed as K_s cos 20 degrees, and this plus 4 - 1, 2, 3, 4. So, 4 W_d, 3 W_d, 2 W_d, 2 W_d. So, the 2, 2 are acting here. So, that is why, I have taken this.

This one has no role. So, that way this is the bending moment due to all these vertical forces starting from this end to this point. Then the weight is acting downward. So, $(W'/2) \times b_m/4$, if the total width of the machine is b_m. That means, from here to here if it is b_m. So, this is $b_m/2$. $b_m/2$ is this one - this distance, and the half of that is $b_m/4$. So, that is why I have taken $b_m/4$.

So, that will give you the total bending moment acting. Now, the shaft is subjected to both bending as well as torsion. So, then we have to find out the torsional component - the torsional moment. So, for finding out K_s cos 20 degrees, I have given the procedure - total peripheral force divided by the number of blades, then multiplied by cos 20. Then, for finding out the torsional moment K_x maximum, which is nothing but your K value - peripheral force divided by the number of blades. Here, the number of blades will be the blades which are in contact with the soil. So, at a time, you have taken 12 number of blades to be in contact with the soil. So, that is why, the K_{max} value will be peripheral force divided by 12. Then, R is the rotor radius, and if you take directly the rotor radius, you are taking a higher value. So, what we can take is a little lesser than that because some portion is used for mounting the blades on the disk.

You can take directly as the rotor because it is mounted. So, you can take directly as the rotor radius. So, now, because of both bending moment and torsional moment, the shaft, which is subjected to both bending and torsion, will create a stress, which will be equal to $\frac{M_e\, y}{J}$. M_e is the equivalent moment acting on the shaft, which is nothing but $(K_m \times BM)^2 + (K_t \times TM)^2$, that means, $\sqrt{(K_m \times BM)^2 + (K_t \times TM)^2}$. I have taken K_m and K_t as the shock and fatigue factors. So, we have taken it as 1.5 for both cases, and then you can find out the polar moment of inertia. The section of the shaft is circular - the cross-section is circular. So, if you are taking a solid shaft, then it will be $\pi d^4/32$ - the polar moment of inertia. And if you are taking a hollow section, then the polar moment of inertia for a hollow circular section is $\pi d_o^4(1 - t^4)/32$, where t is the thickness, and d_o/d_i = t. And y is nothing but the distance of the extreme fiber from the neutral axis, which is equal to d/2. For a hollow shaft, it is $d_o/2$, and for a solid shaft, it is d/2. So, this is about the shaft design.

Then, coming to the blade design, first you have to identify what are the forces acting on the blade. And then, how these forces are going to create bending, torsion, or either bending. So, if you look at the figure, you can see the blades are mounted to the disk or the unit, which is fixed on the shaft with the help of a bolt. So, these are the spaces - holes are provided through which the blade will be mounted to the shaft, the disc provided on the shaft. Now, the force which is encountered - we are considering the L-type blade - then the force which is encountered is the horizontal force K_h. So, the horizontal force, because of that, there will be bending. If you look at this figure, there will be bending, and the bending moment would be equal to $K_h \times S_1$. S_1 is the distance from the tip of the tool to the bottom side; this is not equal to R.

Now, if you look from the front, then the same K_h will try to give a twisting effect, that means a torsional effect. So, what is the torsional moment? So, K_h, assuming that the resultant K_h is acting at half the width of the blade. So, K_h × this distance s, where s is nothing but equal to half the width of the blade. So, for finding out K_h - first, we have to find out the peripheral force, then we have to take the factor of safety. If it is a stony soil, the factor of safety is 2. If it is stoneless soil, then the factor of safety is 1.5. So, we find out from here, after calculating the peripheral force, we find out Kh taking the factor of safety into account. Then from there, how many number of blades are acting at a time if you know, we can find out the peak force acting on the blade. And then we can find out the bending moment, then the torsional moment. $K_h = F_e \sin(\alpha + \psi - \Delta\delta)$. So, that we can take as F_e directly and S_1 is R minus r. R, radius minus the outer radius of the shaft, and then space provided. So, these are to be deducted from the total radius of the blade to find out S_1.

So, torsional moments - in the same way calculate - $K_h \times S$, but S will be equal to half the blade width. So, that way we calculate the torsional moment. Then, the stress due to torsion will be this expression: $TM \times h_e/2$ by the polar moment of inertia. Assuming the cross-section of the blade as rectangular with the thickness be and width - the blade width h_e. Similarly, stress due to bending will be BM by z, that means, bending moment by section modulus. So, $b_e h_e^2/12$ and $h_e/2$ that way you are getting $b_e h_e^2/6$.

Then, assuming a ratio between h_e and b_e as 3 is to 1, then total torsional stress, due to torsion, stress due to bending will be expressed in terms of b_e. And then shear stress, we have to utilize the maximum shear stress theory, which says $\tau_{max} =$

$\frac{1}{2}\sqrt{(2 \times BM \times 1.5/(3 \times b_e^3))^2 + 4(\mathrm{TM} \times 0.6/{b_e}^3)^2}$, So you have the expression for τ_s. You have the expression for σ_b, then we can take the maximum design stress - allowable design stress is 50 Mega Pascal. Then substituting here, we will get an expression in` terms of b_e and then from there you can find out what will be the dimension of b_e. For designing different components, what we can come to a conclusion is it depends on soil resistance. And soil resistance is acting on the rotor blade. For computation of soil resistance, you have to follow a certain procedure.

The procedure is, first, you have to find out the specific work, then the tilling pitch. For the computation of tilling pitch, we need to know the rotor radius, peripheral speed of the blade, forward speed, and number of blades of the disk working in one plane. These are to be finalized for deciding the tilling pitch. And then, utilizing this equation, we can find out the value of l, then we can find out the value of u/V ratio, and then we go for calculating the specific work. Which is equal to A_0 plus A_B. For the calculation of A_0, we need to know the value of C_0. These are given in tables, and the range varies from 2.5 to 3.5. k_0 is the specific soil resistance, that means, unit draft. So, these values are also available. So, you can take this value, then from there you will calculate the A_0 value. Similarly, C_0 and $\boldsymbol{\alpha}_u$ value, you can take from this table and then compute the A value.

Then, after computing the A value, you substitute it in this equation. So, this is the equation for finding out the specific work. So, there, what we know is the A value, we know Z, l, A, b_m also we know, because we have decided the number of blades. Then, find out the value of M. From M, which is nothing but the torque, and the peripheral force will be equal to M upon R. So, the rotor radius is known, from there, we will find out the peripheral force, then you find out the component K_x, and we will also find out the component K_y, and then we can go for designing. Now, how to find out what is the total power requirement for operating a tractor-drawn rotavator?

So, the power requirement for operating a rotavator to carry out tillage is equal to the power requirement for cutting and throwing the furrow slice, then the power requirement for moving the tractor and implement forward. These are the two power requirements. Now, the power requirement for cutting refers to PTO power, whereas, the power requirement for movement, that means, moving forward, depends on the drawbar power. This is called the drawbar power requirement. So, there are two different power requirements. One is PTO power, and the other one is drawbar power. Now, motion resistance you can assume as 8 per cent of the total weight, the weight of the implement as well as the tractor.

So, 8 per cent of that will give you the total rolling resistance. And if you know the forward speed, then you can immediately calculate rolling resistance into V, and 75 is for finding out in terms of HP. So, that way we are getting the drawbar power requirement. Now, if you want to—because you cannot just add drawbar power with PTO power, though I have given in the equation—you cannot simply add it; you have to make the power either drawbar power both or PTO power both. So, that is why what I have done is the drawbar power, which I get from this equation, has to be converted to PTO power—equivalent PTO power. So, how do I convert?

I convert by dividing with a power transmission efficiency. I will come to that in my next slide. So, that efficiency value is available, which is around 0.86 to 0.89. So, if you divide the drawbar power by this value, then we will get the equivalent PTO power. Now, PTO power required for cutting and throwing furrow slices, $P_s = 2\times \pi \times n \times T_{rs} \times$(rotavator shaft rpm/PTO shaft rpm)/60, where T is the torque acting on the rotor shaft. So, n is the rpm of the rotor shaft, and if you know the ratio of PTO to rotor shaft speed ratio and then divide by 60. So, that will give you the total power requirement, a PTO power requirement for cutting and throwing. We have converted the drawbar power to PTO power. So, then you can immediately use it to find out the total power required for carrying out. with a rotavator, but so far you have not considered a power reserve.

So, you can take a 20 per cent power reserve for taking care of odd situations. So, the engine power requirement will be just whatever power you are getting divided by 0.8, and then power transmission efficiency from PTO to engine if you take 0.87 to 0.89. So, that way you can calculate what the total power requirement will be. So, this left-hand side, which I have indicated, will give you a rough idea of how the transmission efficiency is changing or varying from the engine to different power outlets, that means, the drawbar power outlet and the PTO outlet. So, this will, and if you want to go from drawbar to PTO, this is the ratio, or if you want to come from PTO to drawbar, this is the ratio.

To drawbar, multiply; if drawbar to PTO, just divide it. So, this is how we will calculate the total power requirement. These are the references, and the conclusion I can say is we discussed how to arrange the blades, then what the different components are like blade and shaft design, and how to compute the power requirement for operating a rotavator.

Thank you.