Design of Farm Machinery

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Lecture 16 : Design of a tractor drawn rotavator

Hi everyone, this is Professor H. Rahman. I welcome you all to this SWAYAM NPTEL course on Design of Farm Machinery. Today I will discuss about active tillage implements - how to design a tractor drawn rotavator. This is lecture number 16. The concepts which will be covered they are salient findings helpful for designing a tractor drawn rotavator, then design of a tractor drawn rotavator and how to find out the power requirement for operating the rotavator.

So, some of the findings which are useful while designing a rotavator, they are : energy requirement for rotary tilling decreases with increase in velocity ratio, velocity ratio means peripheral speed of the rotor to forward speed of the tractor or the implement. Then the specific energy requirement for cutting soil fast decreases with increase in forward speed and then it increases with further increase in forward speed. That means, you have to have a minimum speed at which you will get the maximum benefit in terms of specific energy requirement. Specific energy requirement is nothing, but the energy consumed per unit area watt hour per hectare. Lower rotary speed and slow forward speed of tractor reduce the draft and power requirement of rotary tillage implements. A faster rotation of the rotavator shaft causes a re-tilling of soil leading to extra power consumption.

That means, we have to find out a suitable RPM and a suitable forward feed. Then decrease in rotor speed results in decrease in PTO torque. In rotary tilling, severeness on the PTO shaft increases with increase in PTO and tractor speed. When PTO speed is increased that means, the blade is striking the soil at a higher force that is why it may affect the dimensions of the that means, design of the blade. Then the negative draft negative draft developed by the rotavator increases with decrease in velocity ratio. The reason is : the longer the bite length and interaction of blades with the undisturbed soil that will develop a pushing force which is against the direction of draft. So, that is why it is called a negative draft that means, force required to pull the implement forward will reduce.

Now I will start with the design of a concurrent mode rotavator for a 45 HP tractor. So, before designing, we should have the idea, how the power is transmitted in a tractor from the engine to the drawbar and from engine to the PTO. So, that will give you an idea how much power is lost or where the power is lost. In case of a rotavator whether it is in concurrent mode or in reverse mode, we take power from PTO to rotate the shaft and we require power to propel the tractor and implement forward. So, we require two types of power : one is related to drawbar power the other one is related to PTO power. So, let us now see, how to calculate the peripheral force or the power available at the PTO? From where we can calculate how much peripheral force is available. Now, engine power to PTO power if you look at the figure there is a transmission efficiency of 87 to - 0.87 to 0.90 that means, if engine power is E then maximum you can get 0.9 E at the PTO. So, you have to take a transmission efficiency and in addition to transmission efficiency you have to take a power reserve and power transmission losses when it transmits power through gears or through chain and sprockets. So, there will be some transmission losses and that we have taken as 20 per cent together.

So, after getting power from the engine this has to be multiplied. So, that means, this is the power available. A 45 BHP tractor it will be multiplied with 0.87 to get the power at the PTO and we have taken the 20 per cent power reserve. So, that way you are getting a power availability of 31.32 HP or 23.36 kilowatt. Now assuming the rotor diameter, rotor diameter means from the center of the shaft rotor shaft to the tip of the blade that is radius. So, twice of that becomes your rotor diameter and you have to assume an u by V ratio. I will come to u/V ratio later on what is its importance. So, now I can - this much I can tell that u/V is 5 that means, it will give you lesser fluctuation in cutting speed.

So, you have to take a minimum value of 5. So, D as 50 centimeter and u/V as 5 centimeter, then the forward velocity of tractor we have assumed as 4 kilometer per hour. So, which is equal to 1.11 meter per second. Now, the tip peripheral speed of the rotor that means, peripheral speed of the blade will be equal to 5.55 that we have calculated taking the radius, rpm and divided by 60. Here the rpm we have taken as 210, because what we have done is - we have initially assume the u/V value and assumed the forward speed.

So, from there we calculated u value and from u value we calculated, what should be the rpm of the rotavator. So, that is why you are getting a 211.9 and that means, 210 rpm. So, power requirement to move both tractor and implement that is to overcome rolling resistance. So, roughly you can assume a value of 8 per cent of the total weight of tractor and implement. So, knowing the forward speed and the rolling resistance we can find out what is the drawbar power required to propel the tractor and implement forward. So, drawbar power requirement will be equal to rolling resistance into forward speed. Assuming a total weight of tractor and implement as 2550 kg. So, 2550 into 0.08 that means, 8 per cent. I have converted into Newton. So, that way you are getting this much watt of power which will be required to overcome rolling resistance. Now, this is a drawbar power now we have to either convert it to PTO power or the PTO power which you get while operating the implement, you can convert it to drawbar power.

So, what I have done is - I have simply converted the drawbar power to PTO power. So, you have to take a transmission efficiency So, whatever power you are getting here divided by the transmission efficiency, that will give you the power equivalent - PTO power - equivalent PTO power of drawbar power to overcome the rolling resistance. Here, the transmission efficiency we have taken as - between 0.86 to 0.89. So, if I take the minimum one - the 0.86, then that way you are getting a power requirement of 2583 watt.

Now PTO power available for cutting and throwing furrow slices. So, that way we are getting whatever power is available at the PTO we have calculated, Then this is the power which is required for propelling the implement and tractor forward. So, if you take the difference that will be the power available for cutting and throwing. So, which is around 20.78 kilowatt. So, if you know the - if you know the rpm - rpm of the PTO is 540 or 1000 whatever you fix it, then from this power you can immediately calculate how much will be the force - peripheral force at the PTO. So, $2\pi nT/60$. So, n you can ah take as 540 and T you have to calculate. Now, what is the torque available at the PTO, the same thing I have done. So, this comes to around 368.4 - 368.4 that means, here I have taken PTO rpm as 540 and this was the power available at the PTO. The rpm of the PTO I have taken 540. So, that- that way we are getting a torque of 368.4 Newton meter, but power is transmitted from the PTO to the rotor shaft with 2 - using 2 gears. So, that means, we are reducing the rpm, rpm we just now calculated the required rpm of the rotor shaft is 210. Now, the 540 rpm has to be reduced to 210. So, we require a gear box. We require in fact, 2 gear boxes, one is for transmitting the power at 90 degree that is the bevel gear, the other one is transmitting the power from the bevel gear to the rotor shaft.

So, torque available at the rotor shaft will be equal to torque which is available at the PTO which is denoted as T then gear reduction. So, here it is 540 by 210 then transmission efficiency may be say 0.9 - losses is 10 per cent so, 0.9. So, that way, we are getting the power available at the rotors - sorry, the torque available at the rotor shaft is 852.58 Newton meter. Now, if you know the rotor radius then you can find out what is the force available at the rotor shaft.

Next thing is the calculation of number of blades and width of the rotavator that is important. So, for calculating this, we have to utilize the specific work equation. Specific work is A, A is equal to - it comprises of two components one is a static component, the other one is dynamic component A_o is the static component, A_B is the dynamic component. Now, for calculating the static component we are using this equation A_o is equal to C_o into k_o, where the value of C_o again depends on the type of soil. If you look at the previous slide here, the values of k_o is given and C_o value you can take from here. For rotary cultivator, you can have value starting from say 1.5 to 3.5 even you can go up to 10 depending on the depth.

So, if it is soil, then you can take a value of 2.5. So, k_o value again we can take from the table which is 0.3 kg per centimeter square. In fact, this is nothing, but unit draft. So, utilizing the value of C_o and k_o you can find out the value of A_o that is the static component of specific work, then dynamic component $A_B = \alpha_u u^2$.

Again you have to take a value of α_u from the table that varies from 300 to 600. So, a value has to be taken. So, that way we have taken 300 for α_u and then peripheral speed we have already calculated as 5.5. Because u/V ratio we have taken 5 and the forward speed is 1.11 meter per second. So, that way u will be equal to 5.55. So, knowing these values then substituting these values in this equation, we can calculate the value of A_B that way you are getting a 9240.75 kg per meter square, kg means kg force. Now, total specific work that means, A_o plus A_B will be equal to 16740.75 kg per meter square.

Now we have to find out the tilling pitch. So, tilling pitch equation is $l = \frac{V \times 60}{N \times Z_e}$. V is the forward speed n is the rpm, rpm of the rotor shaft then z_e is the total number of blades of a disk which are working in the same plane. So, let z_e be equal to 3 that means, 3 blades will work in the same plane in a given set. So that way, forward speed we know then rpm we have taken as 210. z_e value we have taken as - z_e is equal to 3. So, that way you are getting 10.57 centimeter.

Now, the specific work done is equal to 2 pi into torque, T_{rs} divided by volume of soil handled. That means, specific work is defined as work done per revolution of the rotor shaft per unit volume of soil handled. So, that definition I have given in the form of equation $\frac{2\pi T_{rs}}{abl(iZ)}$, where T_{rs} is the torque acting on the shaft - rotor shaft, a is the depth of operation b is the blade width here you have taken or you have you can assume a value from 10 to 15 centimeter. So, you have taken 10.5 centimeter of the blade width. Then i is the number of disks or sets on which the blades are to be mounted. There will be group of sets which will be mounted on the rotor shaft and then Z is the number of blades on each set. So, which is equal to twice the value of Z_e, Z_e is the number of blades which are working in the same plane in a set. So, if I substitute the value of specific work done which you calculated in terms of A_o and A_B and then torque you have calculated from the power available at the PTO and then converted into the power available at the rotor shaft. So, from there you got the torque value of 852.58. Now, substituting a as 10 centimeter blade width as 10.5 centimeter and tilling pitch is just now we calculated as 10.57 centimeter then iz which will be the total number of blades - i into z this is the total number of blades that comes to 30 - 29.39. So, roughly you can take as 30. So, these 30 blades are to be arranged on the shaft. How do you arrange it? So, you have to maintain an angular interval between blades theta - if you denote it as theta - this will be equal to 360 by i z. So, 360 by total number of blades.That way 12° that will be the angular distance between two adjacent blades striking the soil surface. So, 30 blades they are to be - and I have already taken that each set is handling 6 blades : 3 in one direction 3 in the other direction. So, 6 blades in one disk or on on one set. So, so you have to have minimum 6 disks.

3 blades each on the extreme end 2 disks and 6 blades in the intermediate disks and with a gap of 1 centimeter between 2 adjacent - between 2 adjacent sets or disks. Then you can decide the total length of the shaft as 10.5 10.5 this refers to the 2 ends then these are the middle ones. So, all together will get a value of 1.36 meter. Now, after deciding the number of blades and the length of the shaft, then we have to go for designing the blade. Sorry designing the shaft then we are going to design the dimensions of the blade.

So, for calculating the dimensions of the shaft or dimensions of the blade we need to know what are the forces acting. This figure shows what are the forces acting. When the blade strikes, the soil resistance which is denoted as K will have two components K_x and K_y, K_x is the horizontal component and K_y is the vertical component. This K_x is going to act on the shaft as well as on the blade and K_y is going to act on the shaft. So, how to find out K_x and K_y? K_y is the vertical component = K cos $(\alpha+\psi-\Delta\delta)$. So, that is equal to $\frac{M}{R'}\cos(\alpha+\psi-\Delta\delta)$, but we have assumed this R’ as R. So, that way K_x will be equal to K sin $(\alpha+\psi-\Delta\delta)$. Similarly, K_y = K cos $(\alpha+\psi-\Delta\delta)$ and the value of ψ is taken as 15° to 20°. and $\Delta\delta$depends on u/V. So, we will discuss these things later little bit. Then in concurrent revolution - the blade comes in contact with the soil - a single blade comes in contact with the soil at an angle of 20° and it will continue up to 100° that means, the time at which it strikes the soil is 20°. And the horizontal component if you look at this equation - this horizontal component will be maximum when this angle is 90°.

So, we have taken - we are designing for the maximum value. So, you can takes this as 90 degree. So, K_x will be equal to K. There is a peripheral force acting on the blade. Similarly, for the vertical component K_y, this component will be maximum at 20°, 20° because the blade comes in contact with the soil at 20°. So, you can take K_y as K cos 20°.

So, now, you see the arrangement of blades. There will be 6 sets. The last 2 sets you can see 3 blades 1, 2, 3 - 1, 2, 3 and the rest 4 they are provided with 6 blades 1, 2, 3 on this direction, 1, 2, 3 in the other direction same is the case for this, this and this sets. So, now, after arranging the blades next thing is we have to find out what are the forces acting. The gang will have its own weight or the weight of the rotavator, we can take as W dash, then total width of the shaft we have taken as Bm and then because of the vertical forces which are acting at the each blade when it is striking. So, at a time there will be say one fourth - maximum - one-fourth of the total number of blades will be engaged - will be engaged with the soil that means, we have 30 blades, so, 30 by 4 that way it comes around 7.5. So, roughly around 8 blades will be in contact with the soil. So, now, in 8 blades they will be exerting the vertical forces. So, there are 6 if you look at 1, 2, 3, 4, 5, 6, then I have taken 1 blade extra here, 1 blade extra here. That means, at the 2 extreme ends that there will be 2 blades striking the soil surface. Weight is acting downward, vertical forces acting upward. So, then you have to find out, and the shaft is supported on the bearings. So, we have to find out the support reactions R_1 and R_2. So, R_1 and R_2 can be calculated after knowing this value that means, W' minus this is the vertical force divided by 2. So, that way you are getting in 114.42. This is in Newton. Now, how this forces are going to create bending because shaft will be subjected to bending because of the vertical forces.

So, if you take a bending moment about the central axis which is denoted in red colour. So, the bending moment will be equal to R 1 into this distance, from here to this distance which is 2.75 times W_d, W_d is the distance between 2 adjacent sets. Similarly, K_s cos 20°, which is nothing, but K_v. So, twice $K_V \times (W_d + W_d + 0.5\ W_d$ that means, 2.5). So, that way I have written 5 W_d. Next is $K_V \times (W_d$ plus $0.5W_d$, so, 1.5 W_d) then third one is W_d into 0.5. So, that way you are getting. So, K_V, I have taken common and then it becomes 5 W_d+ 1.5 W_d+ $0.5W_d$. Now, half of the weight is acting at a distance say $B_m/4$. So, W' by 2 into $B_m/4$.

So, that way we are getting a bending moment of 102.415 Newton meter. Next, thing is we will calculate the torsional moment. The torsional moment is due to the horizontal force which you have taken as maximum force which is acting - the horizontal force is $K_{x\ max}$ which is equal to your peripheral force. So, K sin 90 and knowing the rotor radius and the number of blades which are engaged in the soil, then you can find out, what is the total torsional moment acting on the shaft. Now we know this value, the torque value acting on the shaft divided by the rotor radius and the number of blade that will give you the force acting on each blade.

Then this is the rotor radius, this is the number of blades striking. That way you are getting again this much torque which will be acting on the shaft. So, now the shaft is subjected to both bending and torsion. So, you have to utilize the maximum shear stress theory from there you can see that stress due to shear, $f_s = \frac{M_e\,y}{J}$. Where M_e is the equivalent moment $\sqrt{(K_m \times BM)^2 + (K_t \times TM)^2}$ and y is the distance of extreme fiber from the neutral axis. That means, you have to decide the cross section of the shaft and then j is the polar moment of inertia that again depends on the cross section of the shaft.

Now, usually the shaft of a rotavator is a either a solid shaft or a hollow shaft. So, assuming that the shaft is solid circular then you can find out bending moment. So, polar moment of inertia, $J = \frac{\pi d^4}{32}$, where d is the diameter of the shaft, then the y value is will be equal to d/2. And, then we have taken some factors of T here that is shock and fatigue factor. So, we have multiplied this bending moment. So, K_m and K_t value, we have taken around 1.5. Now, if you are taking a hollow shaft then this is the equation for polar moment of inertia $J = \frac{\pi {d_0}^4(1-t^4)}{32}$. Where t is the thickness not thickness exactly d_o/d_i is t. Then inner diameter of the hollow shaft is d_i outer diameter is d_o. So, t will be equal d_i by d_o Finding out the equivalent moment utilizing this equation, we calculated the equivalent moment to be 1055.433 Newton meter.

Now, substituting in this equation and taking a factor of 2 for the allowable stress. So, now, this becomes the diameter - comes to 4.786 centimeter that means, roughly around 5 centimeter will be the diameter, if it is a solid shaft.

Now next thing is how to design the blade dimensions or how to decide the blade dimensions. So, I have shown the L type blade. So, L type blade means one side it is projected. So, the horizontal force which is acting, that is going to create both bending as well as torsion. So, blades are subjected to both bending and torsion. And assuming the blade section to be a rectangular section with thickness b e and width h e. So, the factor of safety again we have taken, f for calculating the size of the blade, it is 1.5 to 2. 1.5 is for stoneless soil and 2 is for stony soils. So, whatever peripheral force you are getting, so, you multiply with 1.5 times or 2 times depending on the soil condition and then you divide with number of blades which are striking at a time. So, that way we will find out, the force acting on each blade is - horizontal force is 852.58 Newton.

Now the bending moment we have calculated. For finding the torsional moment we have to find out the value of S_1. So, S_1 is nothing, but rotor radius is 25 centimeter minus r, r is your radius of the rotor shaft just now we calculated. And then 5 centimeter you have given the clearance. So, this. So that way it comes to S_1 comes to 15.21 centimeter. Now, find out the torsional moment which is coming to sorry bending moment which is coming to K_h into S_1 and torsional moment will be K h into S. So, Kh will remain same for both the cases S_1 value is to be calculated and S value is half the width of the blade. So, that way, you can find out the bending moment and the torsional moment which are acting on the blade. Now, again applying the maximum shear stress theory, we calculate what is the shear stress developed due to torsional moment, what is the shear stress developed due to bending moment and the cross section we have already assumed as the rectangular one. So, now applying a ratio between h and b as 3 is to 1. So, then shear stress value is coming to this and stress due to bending comes to 86.44 by b e cube. Now, applying this maximum shear stress theory, we can calculate the value of blade as : thickness, b as 1.16 centimeter and h as 3 times of 1.16, that is 3.48 centimeter. So, this is how you have to design - you have to design a tractor drown rotavator. But this is for concurrent mode and what changes will be there when we reverse the mode that we will discuss later.

And these are some of the references. Then in brief we can say we have discussed about tractor and rotator and how to arrange the blades, how have to decide the shaft length and dimension of the shaft.

Thank you.