Design of Farm Machinery

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Week - 02

Lecture 08 : Design of a Tractor drawn Disk Harrow

Hi everyone, this is Professor Rahman from IIT Kharagpur. I welcome you all to this NPTL course on Design of Farm Machinery. This is module 2, lecture 8, where I will discuss the design of a tractor-drawn disk harrow. The concepts which will be covered in this class are: how to find out power availability for designing the disk harrow, then how to calculate draft for a disk harrow, then design of different components of a disk harrow for a 45 HP tractor. So, the problem is, we have to design a single-acting disk harrow for a 45 HP two-wheel-drive tractor. Its weight is 2200 kg, and the weight of the implement comes around 400 kg, and the rolling resistance for both the implement and tractor together can be taken as 8 per cent of its total weight. That is the information available.

Now, to design any implement, whether it is a moldboard plough, disk plough, or disk harrow, does not matter. So, we have to find out, because these are all passive tillage implements, what is the drawbar power available? So, based on that, we have to decide whether the implement sizes which you are recommending, the tractor should be in a position to develop, to pull this. So, to find out how much is the drawbar power available, we should have a clear idea about the power transmission in a tractor.

So, power is transmitted from the engine. So, it goes to the gearbox of the transmission system, from the transmission system it goes to the PTO, and from the transmission system it goes to the axle, then from the axle to the drawbar power through a final drive. So, what we have to know is, what are the transmission efficiencies between these subunits, so that we can easily calculate how much is the power available at the drawbar or at the PTO, if you know the engine power. So, I have given those values. So, from engine to transmission, there is a loss of 2 to 4 per cent, from transmission to PTO there is a loss of say 8 to 10 per cent, and from transmission to axle there is a loss of 11 per cent to 15 per cent, then from axle to drawbar it again depends on tractive efficiency. So, that is a big question. Tractive efficiency is nothing but drawbar power by axle power.

So, the drawbar power which is developed depends on so many conditions: what is the soil condition, what are the operating conditions, that means slip value, and whether the soil is hard, soft, etcetera. So, anyway, the tractive efficiency value has to be known. If you want to convert the drawbar power to PTO power, you can go in this direction again, whatever power you are getting, there will be a loss of say 14 per cent, 11 per cent to 14 per cent. So, this will give you a rough idea of how the power is lost during transmission from the engine to different outlets. Now, since you are designing a drawbar power-based implement, that means the implement has to be pulled utilizing the drawbar power. So, we need to know how to calculate the drawbar power of a tractor.

So, drawbar power available can be taken as power available from the engine multiplied by transmission efficiency, that means, these two and then tractive efficiency. So, if you multiply, then we will find out what will be the drawbar power available. Out of this drawbar power available, some power will be consumed for overcoming the motion resistance, the motion resistance of the tractor and the implement, okay. So, drawbar power available minus the motion resistance of the tractor with the implement. So, that will give you the power available to the implement for pulling.

Now, how to find out motion resistance? In the question itself, I have given that the motion resistance of the tractor and implement together is 8 per cent of its total weight. So, tractor weight is 2200 kg and implement weight is 400 kg. So, the sum of this will give you 2600 kg. And 8 per cent of that will give you the rolling resistance, which comes to 208 kg. Now, forward velocity for a disk harrow, you can go up to 4.5 km/h. So, I have taken the forward speed of operation as 4 kilometers per hour.

So, power required to propel the disk harrow or to move the disk harrow will be equal to 208, that means rolling resistance power consume for overcoming the rolling resistance. So, that way, rolling resistance multiplied by forward speed divided by 75 just to make it in horsepower. So, that way, you are getting 3.08 HP. Now, assuming a transmission efficiency of 82 per cent from the engine to the rear axle and a tractor efficiency of 60 per cent. So, that way, a 45 HP tractor will develop a drawbar power of around 22.14 HP.

Now, this 22.14 HP and this power required to overcome rolling resistance is 3.08 HP. So, the net power available at the drawbar is the difference between these two, okay. So, before taking the difference, what we have done is, we have taken a 20 per cent power reserve for the factor of safety. So, we have taken a 20 per cent power reserve. So, that way, the drawbar power available is this much, 17.71, and out of this, we have to deduct the rolling resistance - the power required to overcome the rolling resistance.

So, that way you are getting 14.63 HP, which is available for pulling the implement. So, we have taken this measure, which I did not discuss in the beginning. But this is necessary to take care of the odd situations. So, this is a reserve. Now, the draft available—since speed is known and drawbar power is - we have computed. So, from there if you substitute, that means, draft into forward speed will give you the drawbar power. So, drawbar power we have computed, and speed we have fixed. So, from there we find out, draft available is 9.82 kilo Newton.

Suppose you are designing a single acting disk harrow with 6 disks in each gang, that means, on the left side there will be 6 disks, on the right side there will be 6 disks, and it will be operated at a depth of, say, 10 cm. And we need to find out whether the implement can be pulled by the tractor or not. Once it is satisfied, then you go for designing the different components. So, since the depth is 10 cm, the first attempt will be what will be the diameter?

So, we know the diameter equation. D = ka/cosβ, where k, is the coefficient varying from 3 to 6 or 3 to 5, or you can take the maximum depth of operation as one fourth of the diameter. So, a value has to be taken. Then, angle β is not applicable to disk harrow; it is applicable only to the disk plough. So, β is the tilt angle here. So, the tilt angle here will be 0. Now, we have taken the k value as 5. So, the D value comes to 50 cm. So, in the market, the sizes available are 51 cm, 56 cm.

So, we have selected 51 cm as the diameter of the disk. The next thing is, what will be the spacing between disks that will decide the length of the shaft? So, spacing between two adjacent disks in the case of a disk harrow is denoted as S. S is dependent on the depth of operation, the diameter of the disk, and the setting angle or the disk angle, the gang angle. So, a is the depth, which we have taken as 10 cm. D is the diameter, which we just now decided to be 51 cm, and θ_0 you can take as 20 degrees. So that way, we can find out the spacing to be equal to 14.74 cm. That is the spacing between two adjacent disks.

So, in a gang of disks, there will be 5 disks - 6 disks: 1, 2, 3, 4, 5. So, the length of the shaft will be, sorry, 6 - 1, 2, 3, 4, 5, 6. So, the length of the shaft will be equal to 6 multiplied by 14.74. So that we are getting just a little space for adjustment. Then we can assume that the length of the shaft will be equal to 90 cm. So, now, we find out what will be the width of cut.

So, for finding out the width of the cut, either you can use the BIS standard or you can use the ASABE standard. The only difference is, in the ASABE standard, we take the total number of disks, and in the case of the BIS standard, we take the total number of spacings. So, I have taken here the total number of disks. So, in a single-acting harrow, there are six disks in one gang. So, there will be a total of 12 disks, so 12 minus 2. So, the equation is $S = \frac{0.95(N-2)S+0.3D}{100}$, where S is the spacing in cm, and D is the diameter of the disk in cm. So, the diameter we have decided. Now, the number of disks we have decided as 12. So that way, we are getting a cutting width of 1.55 meter. So, we have decided the length of the bolt, and we have decided the cutting width. Now, the next question is, how do we calculate the draft requirement?

So, there are two ways by which you can calculate the draft requirement. The first thing is, if you know the unit draft, then you can calculate the draft coming on the implement or the draft to be encountered. So, for calculating the unit draft, we need to know the values of the unit draft, which means it varies from soil to soil. So, you can take the maximum unit draft value. So, 0.25, 0.3, like that.

So, I have taken 0.25 kg/cm^2, and if you know the cross-sectional area of the disturbed soil, then you can multiply it with the unit draft to find out what the total draft required by the implement is. So, the cross-sectional area that is disturbed by the disk harrow - if you assume it to be rectangular - then width multiplied by depth will give you the furrow cross-section. So, the furrow cross-section multiplied by your unit draft will give you a draft of 3801.375 Newton. And the available draft is 9.82 kilo Newton. So, in that way, our design should be safe - safe in the sense that the implement you are proposing can be easily pulled by the 45 HP tractor.

The question is, this is not properly matched. The only thing we are discussing is whether the implement can be easily pulled by a 45 HP tractor for maximum power efficiency; this has to be properly matched. So, we are not discussing proper matching; we are just discussing whether the implement can be pulled by the tractor or not. So, that is one way of calculating draft. The other way of calculating draft is to utilize the ASABE equation. Suppose our data related to unit draft are not available; then, the other alternative is to utilize the ASABE draft equation.

You can see that draft is: draft per unit width or per meter width of cut, $D = F_i\left[A + B\,(S) + C\,(S^2)\right]T$, where S is the speed in km/h, A, B, C are coefficients, specific parameters, and i could be 1, 2, or 3. So, depending on the soil type, if it is fine soil, then we go for an i value of 1; if it is coarse soil, it should be 3; and in between, you can take 2. Now, T is the depth of tillage in cm. So, if you know the values of these, then we can calculate the draft. So, for a single-acting disk harrow, offset disk harrow, or tandem disk harrow, I have collected information related to A, B, C, and F1, F2, F3.

So, if you look at it, we can see that the components A and B have some values for the disk harrow, whereas C is 0 for all three conditions—like for all three implements. So, 86 and 4.5 for a single-acting disk harrow - this is for our design. And a value can be taken depending on which soil you are going to operate the implement. So, you always go for harder soil because that will give you more draft, okay. So, the draft available has been calculated.

So, either you follow the unit draft method or you follow the ASABE method. So, for computing the ASABE method, we need to know the width of cut. So, the draft, which I have just discussed, is per meter width of cut. So, now, if you know the total width of cut, you just multiply and then find out how much is the draft, the total draft experienced by the implement. So, that we are getting 3801.375 Newton, which is for 2 gangs. Now, for 1 gang, the draft will be just divided by 2.

So, roughly around 1.9 kilo Newton. Now, we have to find out the L by V ratio to find out what is the vertical force acting at each disk or on the entire disk gang. So, for finding out the vertical force, again the ratio we have taken as 1.1, which has to be taken from the table which I discussed in the previous class for different gang angles, for different sizes of disks. So, from there, I have taken the ratio as 1.1. So, if you put here, then the vertical force acting for each gang is: the total vertical force is 1727.898 Newton.

And if you want to find out the vertical force for each disk, then divide by 6, that will give you the vertical force, which is acting at each disk. Then, the weight of the implement we can take as 150 to 270 kg per meter of cutting width. So, we have already calculated the cutting width, okay. So, the weight we can take as 270 into 1.5, that way it is coming around 418.5 kg. So, in the beginning, we have assumed that the weight of the implement is around 400 kg.

So, that way you have computed the rolling resistance. So, there is not much difference, you can say we are getting around 418. So, the weight acting is 4105.5 kg, and the vertical force is 288 Newton, 4105.5 Newton and the vertical force, the total vertical force is 1727.898 Newton. So, that way it is beneficial in the sense, the vertical force is acting, that means penetration is not a problem. This has to be satisfied, otherwise you have to put more weight on the implement and that again will increase the rolling resistance.

So, two conditions are satisfied: one is the tractor is able to pull, and the second one is the weight is sufficient so that the implement can enter into the soil. Then, we will go for designing the shaft. For designing the shaft, you need to know the length of the shaft. The length of the shaft we have already calculated. The spacing between two adjacent disks. So, then multiply the number of disks, which will give you the total length of the shaft. Then, what are the reaction forces acting, R_A and R_B?

So, for calculating R_A and R_B, we need to know the forces which are acting. So, the vertical forces at each disk I have indicated, which are acting upward, and the downward force is the weight. So, that way, you can calculate the bending moment because this weight is going to give you the effect of bending. So, R_A and R_B will be equal to the summation of the vertical forces. That means the weight acting downward minus the summation of vertical forces divided by 2. That way, we calculate R_A and R_B. Then, once you calculate R_A and R_B, I have denoted here what are the forces acting on the shaft. So, these are the calculations for the bending moment due to the vertical forces.

The vertical force will cause a bending moment, and the soil force, which is parallel to the face of the blade, will cause torsion. So, the bending moment we have calculated, M_s is equal to R_A into 3 S, if the spacing is S and the distance between the support where the gang shaft or bolt is supported is taken as S by 2 from the last disk, then it becomes $R_A \times 3S + 4.5\ VS$. So, the summation I have taken (this one, this one, this one) together I have taken as 4.5 VS, then minus $W_g/2 \times 1.5\ S$. So, if you substitute the values of S and substitute the value of V, then we find out the bending moment to be 35.9 Newton meter. Now, to find out the torsional moment, you need to know the soil reaction force. So, the draft is acting parallel to the direction of travel, and the soil reaction force is at an angle; that angle is nothing but your gang angle.

So, the gang angle is taken as 20 degrees. So, we know the draft, and we know the gang angle. So, and we know the number of disks. So, you can just simply put it in this equation to find out the total horizontal force acting on the shaft. That horizontal force, the horizontal soil action, will create a torsional moment, and the moment arm will be equal to: if you look at this diagram here. The moment arm will be equal to: this is the center of the disk. So, this distance. The maximum we can take as r, but since we have already assumed that the soil reaction is acting at a height of a/3 from the soil disturbed area, so I have taken $r - a/3$.

So, that way, the torsional moment comes to: since the diameter of the disk we have decided is 51 cm, we are getting 448.196 Newton meter. Now, the shaft is subjected to both bending and torsional moments. So, because of the bending moment and the torsional moment, there will be stresses induced, and those stresses are indicated here. Assuming that the cross-section of the shaft is square. So, for each side b, this is the stress due to bending, and this is the stress due to torsion. Then, applying the maximum shear stress theory, since it is a ductile material, the maximum stress, $\tau_{max} = \frac{1}{2}\sqrt{(\sigma_b)^2 + 4(\tau)^2}$

So, I have given the expression for a rectangle, no, for a solid square section. So, that way, we finally get $\tau_{max} = \frac{3}{b^3}\sqrt{{M_s}^2 + {T_s}^2}$ $or, b = \left[\frac{3}{\tau_{max}}\sqrt{{M_s}^2 + {T_s}^2}\right]^{1/3}$. Now, if you want to take some factor of safety. So, for the bending moment and torsional moment, we can take shock and fatigue factors. Since the soil condition is not uniform, it is better to take the shock and fatigue factors.

So, that I have taken as 1.5. Then, we have assumed tau max as 150 Mega Pascal. So, taking another factor of safety of 3, the allowable design stress is 50 Mega Pascal. So, now, if I substitute in this equation, we can find out b will be equal to 0.034 m, which means 3.4 cm. This is a fairly good dimension. So, the dimension of the gang shaft is a square bar - a solid bar.

So, this is 3.4 cm, and this is 3.4 cm. Then, we go for designing the frame. The shaft is supporting the disks, and the entire gang is supported on a frame. So, the frame is subjected to torsion due to draft and is subjected to bending due to vertical forces, okay. So, again, we apply the maximum stress theory, and this is the bending stress, stress due to bending, and stress due to torsion. Then, we utilize the maximum shear stress theory. So, these are the forces that are acting.

So, R_A and R_B are due to the vertical forces which are acting. W_g is the entire weight of the gang. So, divided by 2, it will be concentrated at half the distance from here. If you take the central line as this one, then to find out R_A, we need to know the weight acting and the number of disks. So, the maximum bending moment due to vertical forces will be M_f, which is equal to R_A. We have already calculated the same R_A value earlier, which you can use, okay.

So, M_f is equal to 3 times R_A, R_A multiplied by S plus S plus S by 2 here, plus S by 2 here, so that makes 3S. $3R_AS - \frac{W_g}{2} \times 1.5S$. So, the horizontal force tends to produce a twisting effect on the frame, and the moment due to this force will be the torsional moment, equal to $D_f/\cos\alpha$ because D_f is this one. $D_f/\cos\alpha$ is the soil reaction force. So, $(D_f/\cos\alpha)\times(D - a/3 + \text{clearance})$. While calculating the bolt, we have taken only up to this, $D - a/3$, because the center of the disk is on the gang. Now, the frame is slightly above. So, that is why you have to take this clearance and then multiply $D_f/\cos\alpha$ by N1, which will give you the total horizontal soil reaction, multiplied by this moment arm, which will give you the torsional moment. So, again, assuming the frame to be a solid square section, there is stress due to bending and stress due to torsion. So, we calculated using this formula, assuming that the sides are of size b. So, applying the maximum shear stress theory, we calculate b as this much, and then substituting the values for K_m and K_t, which you have taken as shock and fatigue factors as 1.5, and the bending moment and factor of safety for allowable stress as 3, so this will be the expression.

And then, we have computed the bending moment of the shaft, and then we have computed the torsional moment. So, this comes to this value, this comes to this value, and then substituting in this equation, we finally get an expression for b as this much, and the total value which comes to 4.734 cm. So, these are the references, and the conclusion is that the design of components of different disk harrows has been discussed for a given size of tractor.

Thank you.