Design of Farm Machinery

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Lecture 48 : Working principle of harvesters

Hi everyone, this is Professor H. Raheman. I welcome you all to this NPTEL course on Design of Farm Machinery. This is lecture 48, where I will try to cover harvesting equipment, how to classify different harvesting equipment, then what are the different working principles, and what are the different components that we will discuss in this class.

The basic thing is, what is harvesting? Harvesting is nothing but gathering the important portion of the plant. So, how do you do it? By simply cutting it. So, harvesting is the cutting process carried out when the crop attains physical maturity such that maximum recovery of quality product is obtained. So, to draw maximum benefit from the crop, harvesting has to be done at the right time to minimize the field losses. That is important. Then, this is important with respect to cereal crops or legumes, and then, as I said, harvesting is nothing but gathering the important component, which means how do you gather it? By cutting it. So, the figure which I showed is the traditional cutter predominantly used in India, which is the sickle. There are different varieties of sickles. So, basically, a person has to hold the bunch of crop, then he has to shear it by moving the other hand with the sickle. So, if you try to classify the cutting mechanism, cutting could be by impact or cutting could be by shear. So, when you are using an impact cutter, it has a single high-speed cutting element and it relies primarily upon the inertia of the material being cut to furnish the opposing force required for shearing.

When you apply a shearing force, it has to be opposed. So, that opposing force has to be provided by the inertia of the material to be cut. In order to have cutting by shear, a system of forces must act upon the material in such a manner that it causes the material to fail in shear. Shear failure is always accompanied by some deformation in bending, in compression, which increases the work required for cutting. So, during the shearing process, such deformation will occur, requiring more power to carry out the cutting operation.

Now, let us see what are the different harvesters available. The one which I showed now in the slide - there, harvesting is done by impact, meaning cutting is done by impact. So, the left side is nothing but your lawn mower, which is used for cutting grass. So, this is done by impact. The right side is a rota slasher. This is also for cutting grass or bushy crops. This is also by impact.

The difference is : the power source here, is a small engine; here, the power source is a tractor, and the power is taken from the tractor PTO to operate those blades used for giving impact to carry out cutting. Now, this is also an impact cutter, but it is a flail shredder - it is called a flail shredder. So, a flail shredder means if you look at this figure, there is a central shaft. To this shaft, there are flails attached, either hinged - in fact, they are hinged or connected with the help of loops. So, these flails are working elements; they are of different shapes. I will show you a little later. So, the difference between this kind of flail shredder and this rota slasher or the lawn mower is that here, the axis of rotation is vertical. That means, cutting takes place in horizontal plane. Here, the axis of rotation is horizontal that means, it is perpendicular to the direction of travel. The entire unit has to be rotated just like a rotavator and the elements will strike the surface of the crops and that will try to cut the crops into smaller pieces. So, this is the difference - this is horizontal axis of rotation that is vertical axis of rotation. But both are impact type cutters.

Now the figure which I am showing here is a self-propelled vertical conveyor reaper, tractor-mounted vertical conveyor reaper. Here, cutting takes place by shear ok. So, we need to have a special kind of blade or knife that will try to shear the material to be cut. This is a combine harvester. Again, this is a cutting by shear. So, only difference is it has a bigger unit - cutting unit and the vertical conveyor reaper has a smaller unit as the engine size is small. So, it confined to smaller width of 1 to 1.2 meter and if it is a tractor power - a front-mounted tractor-operated vertical conveyor reaper, then the width is width can be kept same as that of the combined harvester.

So, as I said if you want to gain maximum output from the crop then you have to harvest it at the right moisture content. So, I have given a list of crops which are to be harvested at the moisture content and the harvesting moisture content is given. Then if you carry out harvesting at this moisture content then the losses, particularly, shattering losses are minimized. So, now one will be wondering why we should have different mechanism? Why we cannot utilize the impact cutters for carrying out harvesting operation in cereal crops. The reason is shattering loss. If we carry out cutting in case of cereal crops by impact, the grains will be detached from the panicles and it will fall on the ground. So, it becomes difficult for the farmer to collect those grains. So, that is why we do not prefer or allow impact-type cutting to harvest cereal crops like paddy and wheat.

So, let us now see what the different harvesters are and their working principles for harvesting forage crops or hays. The first one is a flail shredder, as I showed in the beginning figure. The working elements could be of different shapes and sizes. They are hinged to the central shaft, and the central shaft is rotated by taking power from the PTO. As cutting takes place by impact, the peripheral speed must be very high, between 46 to 56 meters per second. So, at this peripheral speed, the working elements strike the surface to be cut, or they can be hinged here. They can either be attached with loops or directly hinged to the central shaft. So, when it hits a hard object, it swings back, meaning it will not damage the structure. So, that is why they are either hinged or provided with loops, and they must be arranged in 3 or 4 rows. So that they can easily cover the total width without any gap between two adjacent working elements. Now, the cutting width varies from 1.2 meters to 6.1 meters, depending on the power source.

Now, if you look at the top figure, there is a shroud here. This shroud basically helps in bending the crop to be cut so that you can minimize the speed of the working element. So, this kind of flail mower is also available. Now, here the question is: the blades are rotating, and the machine is also moving forward, meaning the path traced by the blades is not exactly circular. It is a cycloid. So, I have indicated this path. The dotted lines are the paths followed or traced by these working elements. Now, suppose Vp is the forward speed of the machine, and omega is the angular speed of the working element. Then, in time t, the working element tip has moved from this initial position to this position, and this is the condition.

So, if you move it very fast - the rotor then you will get more or less uniform height of cut. This Z_d indicates the height of cut from the ground. So, if you increase the rpm of the rotor then you will get more or less uniform height of cut. If you increase the forward speed, keeping the rotary speed same, then you may have different heights of cut. So, the distance it covers that we have and how many bites are acting in that distance, that is important in finding out the uniformity.

Now, if you want to find out the tips of the knife - x and z coordinates of the tip of the knife then x will be equal to the distance it has moved because of the forward speed, $V_p \times t$ and at the same time it has gone up to this - angular movement is there. So, r if this is angle is θ that will be equal to ωt. So, then distance covered will be $V_p \times t + r \sin \omega t$. That means, r means r_f that is radius. Now, the vertical coordinate z coordinates will be r_f - now it was here now it has come to this place if you draw a horizontal line. So, the difference is your z coordinate. You are taking z coordinate from the ground. So, $r_f - r_f \cos\theta$, that will be the height. Now the height of cut, $Z_d = r_f[1 - \cos(\pi/(\lambda_r(1+C_v)))]$. $C_v = \frac{V_p}{V_f}$ and λ_r is the number of rows of flails on the rotor. So, θ is the angular movement during time t, r_f is the radius, radius of the tip of the working element and these are the equations which will control how the tip of the tool is tip of the working element is following the path. Then once you decide this you want to find out the power requirement. So, power requirement of a flail mower as it is cutting by impact, so, its requirement is very high compared to your sickle bar mower, where the cutting takes place by shearing. Even if the width is the same, it will consume more power. ASAE has given an empirical equation by which you can find out the power requirement of a flail mower. If you look at this, then the power requirement for a flail mower. $P_{mow} = 10 + 4.0\, \dot{m}_f$, $\dot{m}_f$ is the feed rate of the crop to be cut. So, PTO power is in kilo Watts. Since it is an empirical equation, we have to be very careful in handling this equation, and the feed rate is in kg per second. So, 10 is a constant that will account for bearing friction and the pumping action because it is rotating at a higher speed. So, there will be air resistance. So, all frictional effects are accounted for by this value, 10. Now, what is this feed rate? Feed rate means if you know the forage yield, the crop yield on wet basis, which is given in megagrams per hectare, multiplied by the area covered. Area means - the width of the flail and the forward speed (V_f), then you can find out the feed rate. That means the quantity or mass of material to be handled per unit time. $\dot{m}_f = \frac{Y W_s V_f}{10}$. So, forage yield in Mega grams per hectare multiplied by the area in square meters per second will give you the feed rate in kg per second. So, this is the mass of material to be handled. Once you know the mass, you can calculate the power requirement, but this is not the total power requirement. This is the power requirement at the PTO because you are taking power from the PTO. So, if you want to find out the total power requirement, this has to be added to the power required for propelling the entire unit forward. That means you have to calculate the drawbar power requirement for moving the entire unit forward. So, this is PTO power, and this is drawbar power. So, you cannot just add it to find out the total power requirement. So, they have to be converted to either PTO power or drawbar power.

Now, the figure which I am showing is a rotary mower. There will be, instead of this working element here, there will be number of disks and each disk will carry either 2, 4 or 6 blades. There will be series of disks and they are arranged in such a way that there will be no free space in between. So, the entire width is covered. So, that means there should be some cutting overlap. So, the cutting width varies from 1 to 2.1 meter with a single rotor. So, rotor is, as I said, it is fitted with 2 knives or sometimes 4 knives or if you want more accuracy you can go up to 6 knives also. For wider units you can have 2 or 3 rotors. You can have series of rotors depending on what is the power source available. The power is again taken from the PTO. The peripheral speed is 51 to 76 meter per second, this is little more than what we observed in case of flail mower. Then, power can be transmitted to this disk either on the top or on the bottom. This is on the top side, this is on the bottom side. And the two adjacent rotors they will rotate the blades in opposite directions, so that you will get the clear band of cut crops. If you do not follow this, then what will happen? The entire swath will be covered by cut material. So, it becomes difficult for the collection of these cut materials. So, if you want these cut materials to be in bands, then you have to operate the two adjacent disks or rotors in opposite directions. And the knives which are provided, the entire radius is not used as a knife. Only a small portion is used as a knife, and they are attached to a support arm and can be shaped to create an updraft, which raises the lodged material. So, that will lift the cut material for further size reduction. So, the knives are not directly connected to the central shaft; they are connected to the support arm through vertical hinges. The hinge is provided so that if it strikes a hard object, the blade will not be damaged. It will swing back, preventing damage to the blade. So, this is - so, basically, power is taken from the PTO, and there are cutting blades. That power will be transmitted to the cutting blades. That is the mechanism. Then, when we try to cut by impact, the impact force which is applied - if it is a shear type of cutting, then the impact force has to be supported by a ledger plate. But if it is not a shear type - if it is an impact type cutting, then the force which is applied for cutting has to be supported - supported by two things: the bending resistance, which comes from the uncut portion remaining in the ground, and the inertia of the cut portion of the plant - the portion of the plant which is cut. So, in the case of an impact type cutter, the bending resistance and inertia play an important role.

Suppose in shear cutting we try to increase the gap between the counter-shear plate and the knife; then it will behave like an impact cutting. If the gap is more, then the support will not be provided by the counter-shear. So, the counter-shear type - that means the shear cutting - will be equal to impact cutting if the gap between the knife and the counter-shear is maintained high.

Now, let us see what is the knife velocity that causes cutting in the case of an impact cutter. So, to do that, we have to make some assumptions. Assumption one is that the time of cut is the time required to cover a distance equal to the diameter of the stem, assuming that there is no deflection. Assumption two is that the mass of the plant above the cut is accelerated to the knife velocity. The mass of the plant that is cut is accelerated to the knife velocity. Assumption three is that the cutting force is constant during the course of cutting. The cutting force is constant and does not change. Assumption four is that the bending resistance from the uncut portion of the plant is constant during the cutting process. This means both the cutting force and the bending resistance are considered constant. If that is the case, when you try to cut the crop, you are applying an impact force F_x, which has to be opposed by the bending resistance denoted as F_b. The bending resistance is a function of the stem below the plane of cut, and it must be opposed by the inertia of this material. If the mass of the material is m_p, then the inertia of the material has to oppose this. Now, if the center of gravity is located at this point, which is at a height of Z_{cg} from the plane of cut, and the height of the plane of cut is Z_c from the ground, then by taking the equilibrium of moments acting on the plant, this is the equation. The mass of the plant cut into acceleration, which is nothing but V_k/t. We have assumed that the cut plant gains a velocity equal to V_k, the knife velocity. So, velocity divided by t gives acceleration. Mass multiplied by acceleration gives the inertia force from the cut portion, multiplied by the height Z_{cg} plus Z_c, which gives the moment acting due to the cut portion of the plant. Now, the bending resistance is $F_b \times Z_c$. That should be equal to $F_x \times Z_c$. Solving this will give an expression for the knife velocity. To clarify further: F_x is the cutting force, m_p is the mass of the plant that is cut, V_k is the knife speed, t is the cutting time, Z_c is the cutting height from the ground, Z_{cg} is the height of the center of gravity from the cutting height, and F_b is the bending resistance of the uncut portion. Now, if you want to express time in terms of known parameters, the known parameter is the diameter of the plant stem. So, you know the knife velocity. So, from here we can find out how much time will be required to cover the distance that is equal to the diameter. So, d/V_k will give you the time. Now, if I substitute this d/V_k in this equation, we finally get an expression for the velocity of the knife, V_k. Now, if you look at this equation, $V_k = \sqrt{\frac{(F_x - F_b) Z_c \times d}{(Z_c + Z_{cg}) m_p \times 1000}}$, if F_b is equal to F_x, what will happen? Whether cutting will take place or not? Cutting will take place. That means we do not have to operate the knife, we do not have to reciprocate the knife, or we do not have to give an impact force to the knife. Simply dragging a blade over the crop is enough to cut the plant. So, knife velocity is required when the bending resistance is low. If the bending resistance - that means, if the stump which will be left after cutting is strong enough, then you do not have to give an impact force. Simply dragging the blade over the crop is sufficient.

In the non-rotating u, v coordinate system, we have to find out the velocity in the u and v directions, the velocity of the tip of the blade. So, $V_u = V_f - r_b\omega_b \sin(\omega_b t)$. That means, in time t, it has moved a distance. So, that is $\omega_b \times t$.

Now, $V_v = r_b\omega_b \cos(\omega_b t)$. Now, the angle of obliquity, $tan\emptyset_{ob} = \frac{V_f\cos\theta}{V_p - V_f\sin\theta}$. So, $\emptyset_{ob} = tan^{-1}(\frac{V_f\cos\theta}{V_p - V_f\sin\theta})$. Now, during time t, the velocity - because of the velocity, the machine is moving forward - so, it has covered a certain distance, and that distance has to be occupied - that means, taken care of by these two blades, if you concentrate on this figure. So, the distance traveled will be equal to V_f, the forward speed, multiplied by t. Now, this distance has to be taken care of by the blades, number of blades present. So, I can write this as $V_f \times 2\pi/\omega_b$, where, ω_b is the angular speed of the blade. Now, there are two blades. So, this has to be divided by number of blades. So, this will be the expression for finding out what will be the length of blade.

Now, if you have more number of blades this length will reduce. So, this is the minimum length of the blade which is required. That means, this has to be covered by anyway. We can have more than that. The length of the blade can be always kept more than this, but this is the minimum one we have to keep it. And this will reduce as the number of blades will increase. That means, if you take 4 it will further reduce. So, L_a is the advance per blade passage which is in meter and λ_b is nothing, but the number of blades on each disk or drum. So, the tapered angle β can be calculated - $\beta = \tan^{-1}\left(\frac{V_f}{\omega_b r_f}\right)$ that means, $\frac{V_f}{V_p}$. So, the next question is we have decided the length of the blade which should be greater than minimum length or the distance the machine is moving per blade. The tapered angle which has to be provided we have calculated, how to calculate I have given. Then what is the maximum width it is covering? So, assuming that it is covering the total radius, so the swath will be twice r_b. If you want to complete cutting then you have to have some overlap and the disks of adjacent drums have to be arranged in such a way that the spacing should overlap. And the blades are arranged in such a way that they should not strike each other. The blades of adjacent disk should not strike each other.

So, these are some of the design considerations. Then for power requirement again, since this is operated by tractor PTO. So, the total power requirement - PTO power requirement that means, for rotating the mower this is the expression. $P_{mt} = (P_{ls} + E_{sc} \times V_f) W_c$. That means, a component, this is one component. This component is again dependent on the width of cut and this component is also dependent on width of cut. That means, if you divide this, power requirement for cutting comprises of idle power plus useful power. Useful power means power requirement for only cutting which is called absolute cutting and to do that we need the cutter bar to be rotated at a very high speed. So, when you are rotating at a very high speed, air resistance will be there, friction will be there, friction between crop and blade will be there. So, all those will be taken care of by this component. So, that is why they have divided into two components just like in case of a flail mower.

There we have given a formula - ASAE has given a formula, 10 + 4 $\dot{m}_f$. So, this this constant is here represented by P_{ls} into W_c. That means, P_{ls} is the specific power loss due to air, stubble and gear-train friction. This is given as kilo Watt per meter. So, and E_{sc} is the specific cutting energy that means, cutting energy per unit area. When we know V_f forward speed W_c is the width of coverage that when you multiply that one with E_{sc} that will give you directly the energy which is consumed, the power which is consumed not energy - power which is consumed. Now, this is the value of P_{ls} is given as - this is between 2 to 4 kilo Joule per meter - kilo Watt per meter sorry kilo Watt per meter.

And for Esc, the value is between 1.5 to 2.1 kilo Joule per meter square. So, if it is a sharpened blade then you go for the minimum value, if it is a blunt blade you go for the higher value. So, if you substitute here then finally, you will get kilo Watt because this one is already in kilo Watt, this one Vf is in meter per second. So, that will give you kilo Joule per second. So, that way you will get kilo Watt.

Usually the disk size is 0.4 meter that means, swath for a single disk is 0.4 meter and it rotates at a rpm of 3000. The knife speed is 60 to 70 meter per second and it could be it could have 3 to 7 disks in a row. So, let us now solve this problem so that will give some more clarity.

Each disk in a rotary mower carries 4 blades and rotates at 2500 rpm and each disk is to cut a swath of 0.45 meter. If the maximum travel speed is 15 kilometer per hour, calculate the minimum required length of each knife. Then select an actual blade length and base diameter of each disk onto which the knives are to be attached. Then finally, calculate the minimum taper angle on the end of each blade.

The first thing is calculate the minimum required length, which is nothing but $L_a = V_f \times 2\pi/(\omega_b \times \lambda_b)$. So, V_f is given as 15 kilometer per hour. We can convert it to 15000 by 60 that becomes meter per minute and λ_b is given as - this is to be cut by four blades, lambda b is 4. Then omega, 2500 is given. So, ω_b will be $2\times \pi \times 2500$. So, if I substitute here, then L_a becomes 0.025 meter. So, 2.5 centimeters is the minimum required length of the blade. So, select an actual blade length. So, you can select either 2.5 or 3 centimeters; it does not matter. So, but this should be the minimum.

So, you can select, say, 3.5 centimeters, suppose. Now, the base diameter of each disk onto which the knives are to be attached, that means the total swath is given as 0.45. So, 0.45 minus, if you consider the blade length as 3.5. So, minus 3.5 multiplied by 2, divided by 100. So, this is in meters.

So, that way, you will get that means $0.45 - 0.07$. That will be the base diameter. Now, finally, calculate the minimum taper angle. For calculating the minimum taper angle, we know that $\beta = \tan^{-1}\left(\frac{V_f}{V_p}\right)$. So, V_f is given as 15 kilometers per hour.

So, 15 into 1000 by 60, and Vp is nothing but your ω r. So, r is 0.45 by $2 \times \omega$, $2 \times \pi \times 2500$, because I have kept meter per minute. So, tan inverse this one. So, that way you are getting 0.696. This is in radians; I converted it to degrees. So, 4 degrees around. This is the answer. That is all.

These are the references, and finally, I can say we discussed the harvesting equipment, their classification, their working principles, and we discussed with respect to the harvesting of forage crops, not the cereal crops.

Thank you.