Precision cut forage harvester chopper units and particle length distribution

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Abstract: The main schemes of precision cut forage harvester chopper units were considered. The method was enhanced for evaluation of particle length distribution for chopped plants provided by cylinder and flywheel type forage harvesters. The effects of the theoretical length of cut, the width of an open throat of a chopper unit and the whole stalk length on percent mass of particles in different diapasons by length were investigated. The accent was made on the length of particles in the range from 8 to 19 mm, suitable for grass ensiling. The theoretical results did not contradict the recommendations for precision cut forage harvesters to set theoretical cut length when harvesting grass for grass haylage. The forage harvesters of this type provide high-quality forage chopping, when relative mass of particles in the range from 8 to 19 mm by length is in the range from 45% to 75%. Calculations showed that theoretical length of cut should be installed in the range from 7 mm to 16 mm to get these characteristics. The estimated maximal percent mass of particles ranging in length from 8 mm to 19 mm, is achieved when theoretical cut length is about 8 mm.

Keywords: a forage harvester, a chopper unit, particle length distribution

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1 Introduction

Numerous studies show that the chopped feed quality depends on the plant chop quality (Bal et al, 2000; Bhandary et al, 2008). The quality of plant chopping provided by a forage harvester, is defined by particle length distribution. It is important to find the theoretical basis of plant chopping regimes for grass haylage and other kinds of feeds. Chopping is the main operation what forage harvester has designed for. Other operations are auxiliary: delivering crop into a chopping unit and diverting crop from a chopping unit.

Chopping systems of modern forage harvesters can be classified in a traditional way: non-precision cut and precision cut chopping systems. Precision cut chopping system has feed rolls. Such a system is presented by four designs: 1) a cylinder cutterhead and a separate throw crop accelerator; 2) a cylinder cutterhead and a separate blower with an auger between them; 3) a cut and throw cylinder cutterhead; 4) a flywheel cut and throw cutterhead.

1. The conventional cut and blow forage harvesters have been modernized. The modern cut and blow forage harvester uses a cylinder cutterhead for crop chopping and a crop accelerator for forage throwing through a discharge spout. Feed rolls 1 press crop and push it through an open throat on a shearbar 2 and into a cutterhead 3 (Figures 1-2). Paddles of a crop accelerator 4 capture forage and throw particles of crop into a discharge spout 5. Two rolls 6 of a kernel processor are installed when there is need to crack and crush kernels and cobs.

2. A cylinder cutterhead altogether with an impeller blower are still used in trailed cut and blow forage harvesters. Feed rolls 1 press crop and push it through an open throat on a shearbar 2 and into a cutterhead house 3...
An auger 6 delivers forage from a cutterhead to a blower 7. A cutterhead house bottom 5 and rolls 4 of a corn processor are installed when there is need to crack and crush kernels and cobs. Recutter screens as optional equipment can be included in a cylinder type non-processor chopper. A recutter 8 is installed in the place 5 between a cutterhead and an auger. Five recutters are available.

3. Nonconventional cut and throw forage harvesters with upper cut system are still used. Feed rolls 1 press crop and push it through an open throat on a shearbar 2 and into a cutterhead 4 (Figure 5). Knives of a cylinder cutterhead cut the crop at the high positioned shearbar and throw it directly into the stout 3 without any friction between crop particles and a cutterhead house walls.

Figure 1 Precision cut chopping system with a cylinder cutterhead and a crop accelerator of a self propelled forage harvester

Figure 2 Precision cut chopping system of a trailed forage harvester

Figure 3 The cylinder type chopper of a forage harvester with a blower

Figure 4 The cylinder type chopper of a forage harvester with a blower

Figure 5 A chopper system with a cylinder cut and throw cutterhead

4. A flywheel-type chopper is used in mounted and trailed forage harvesters. Feed rolls 1 press crop and push it through an open throat on a shearbar 2 and into a flywheel cut and throw cutterhead 3 house (Figure 6). A cutterhead contains radial paddles 6 for better throwing crop into a pipe 4. For better corn cob chopping smooth working surfaces of paddles 6 and bottom 5 are replaced by wavy working surfaces or cracked section plates.

The following forage harvester parameters were used: $D$ – diameter of a cutterhead; $\omega$ – angular velocity of a cutterhead; $W_c$ – width of an open throat of a chopper unit or cutterhead width; $n$ – number of knives of a cutterhead in plane of rotation; $l_c$ – theoretical length of cut (Table 1).
Table 1  Specifications of precision cut forage harvester cutterheads

<table>
<thead>
<tr>
<th>Model(s)/company (reference)</th>
<th>Figure</th>
<th>$D_1$, mm</th>
<th>$\omega$, rpm</th>
<th>$n$</th>
<th>$W_c$, mm</th>
<th>$l_c$, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>FP 230/New Holland (New Holland, n.d. a)</td>
<td>4</td>
<td>533.4</td>
<td>850</td>
<td>12</td>
<td>558.8</td>
<td>4.8/6.4/8.9/11.1</td>
</tr>
<tr>
<td>FP 230/New Holland (New Holland, n.d. a)</td>
<td>4</td>
<td>533.4</td>
<td>850</td>
<td>8</td>
<td>558.8</td>
<td>7.1/9.5/11.1/14.3/16.7</td>
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<tr>
<td>Fp240/New Holland (New Holland, n.d. a)</td>
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<td>850</td>
<td>12</td>
<td>619.8</td>
<td>4.8/6.4/8.9/11.1</td>
</tr>
<tr>
<td>Fp240/New Holland (New Holland, n.d. a)</td>
<td>4</td>
<td>533.4</td>
<td>850</td>
<td>8</td>
<td>619.8</td>
<td>7.1/9.5/11.1/14.3/16.7</td>
</tr>
<tr>
<td>3955/John Deere (John Deere, n.d. a)</td>
<td>3</td>
<td>457</td>
<td>850</td>
<td>12</td>
<td>457</td>
<td>6.0–25.4</td>
</tr>
<tr>
<td>3975/John Deere (John Deere, n.d. a)</td>
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<td>457</td>
<td>850</td>
<td>12</td>
<td>559</td>
<td>6.0–25.4</td>
</tr>
<tr>
<td>FHX300/ Case IH (Case IH, n.d.)</td>
<td>3</td>
<td>533</td>
<td>850</td>
<td>12</td>
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<td>FP-41/DION (Dion -Ag Inc., n.d.)</td>
<td>2</td>
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<td>3</td>
<td>457</td>
<td>850</td>
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<td>559</td>
<td>6.0–25.4</td>
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<td>533</td>
<td>850</td>
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<td>480</td>
<td>1600</td>
<td>6</td>
<td>720</td>
<td>5.7/8.5/10/12/14/16/18</td>
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<td>480</td>
<td>1600</td>
<td>6</td>
<td>720</td>
<td>21/23 (21/25)</td>
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<tr>
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<td>1600</td>
<td>10</td>
<td>900</td>
<td>16 maximum</td>
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<tr>
<td>FCT1360/Kongskilde (Kongskilde, 2018)</td>
<td>5</td>
<td>480</td>
<td>1600</td>
<td>10</td>
<td>900</td>
<td>7/15 standard (6/8 optional)</td>
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<tr>
<td>Mex5/Pottinger (Pottinger, n.d.)</td>
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<td>na</td>
<td>na</td>
<td>na</td>
<td>5/7/9/11/15/19</td>
</tr>
<tr>
<td>Mex6/Pottinger (Pottinger, n.d.)</td>
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<td>na</td>
<td>na</td>
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<td>na</td>
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<tr>
<td>FR450, FR500, FR600, FR700, FR850/New Holland (New Holland, 2018b)</td>
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<td>860</td>
<td>8-44; 6-33; 4-22; 3-16; 2-13</td>
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<td>8100, 8200, 8300, 8400, 8500/ John Deere (John Deere, n.d. b)</td>
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<td>1100</td>
<td>10; 12</td>
<td>678</td>
<td>7-26; 6-22</td>
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<tr>
<td>8600, 8700, 8800/John Deere (John Deere, n.d. b)</td>
<td>1</td>
<td>668</td>
<td>1100</td>
<td>10; 12</td>
<td>851</td>
<td>7-26; 6-22</td>
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<td>5-31; 4-22; 3-17; 2-15; 1-9 (0.5 mm increments)</td>
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<tr>
<td>Big X 700, 770/Krone (Krone, 2018)</td>
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<td>1200</td>
<td>10; 12; 14</td>
<td>730</td>
<td>5/6.5/8.5/11/17/21; 4/5.5/7/9/14/17; 3/4.5/6/8/12/16</td>
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<td>na</td>
<td>na</td>
<td>na</td>
<td>any required</td>
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<tr>
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<td>680</td>
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<td>800</td>
<td>7.4-41.4; 5.2-29; 3.7-20.7; 2.6-14.5</td>
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</table>

2 Theory and methods

2.1 The task

The purpose of this research is to develop an algorithm to assess the particle length distribution for chopped plants on the basis of mathematical model of chopping by a forage harvester, supplied with a cylinder or a flywheel cutterhead. The length of cut has an impact on the chopped forage quality. Current recommendations for grass ensiling are grass harvesting at the theoretical cut length of 6.3 to 12.7 mm to ensure the quality of chopping, at which the relative mass of forage particles in the middle sieve of Penn state forage particle separator is 45%-75% (Jones et al., 2004; Wiersma, 2013). In this case, the length of each particle should be in the range from 8 to 19 mm. The consequent task was to investigate the effects of the theoretical length of cut and the width of an open throat on the percent mass of stalk particles in the range from 8 to 19 mm by length.

The theme of particle length distributions for plants chopped by precision cut forage harvesters is not new (Szendro, 1979; Saqib and Finner, 1982; O'Dogherty, 1984; Morgan et al., 1984; Bietresato et al., 2013). In the above papers, questions of evaluating the effect of the width of an open throat on the length of the chopped forage particles were not considered.

2.2 Denotes

$H$ – the length of the whole stalk between feed rolls, mm; $W_c$ – width of an open throat, mm; $l_c$ – theoretical length of cut, mm; $L$ – fixed value, mm; $M_L$ – the mass of...
particles the lengths of which are in the range from 0 to \( L \), kg; \( M_T \) – the total mass of all particle, kg; \( m_L \) – percent mass of particles in the range from 0 to \( L \) by length; \( m \) – percent mass of particles in the range from 8 to 19 mm by length.

2.3 Calculation of particle length and particle mass

Let us consider the stalk \( MN \) by the length of \( H \) at the moment of entry into a cutterhead (Figure 7).

Let \( l \) be the length of high part of the stalk, \( M(l) \) – the mass of this part. It was assumed that the plant density \( \rho \) per length unit at some point (section) increased directly proportional to the distance \( y \) between the top of stalk and the section:

\[
\rho = a \ y; M(l) = a \ \hat{y}^{2}/2
\]

where, \( a \) – the coefficient of proportionality.

Then the mass of any stalk part the length of which is \( \Delta \) can be calculated by the formula

\[
m(l, \Delta) = M(l + \Delta) - M(l)
\]

or

\[
m(l, \Delta) = a[(l + \Delta)^{2} - l^{2}] / 2
\]

where, \( l \) is a distance between the top of the stalk and the stalk part.

By definition,

\[
m_{L} = 100 \ M_{L} / M_{T}.
\]

It can be seen from the Equation (9), that \( m_{L} \) does not depend on coefficient \( a \). Therefore, it can be accepted \( a = 1 \) for calculating \( m_{L} \) and \( M_{L}, M_{T} \).

By definition,

\[
m = m_{L} |L=19 \ mm - m_{L} |L=8 \ mm
\]

When a forage harvester is equipped with a cutter, the front point \( M \) is the lowest point of a stalk in the feed flow. When the forage harvester is equipped with a pick-up, the front point \( M \) can be the low point or the high point of the stalk with the probability 0.5.

The stalk \( MN \) is cut, if the cut \( MN \) crosses the axis \( O \xi \).

The number \( n \) of the particle parts, formed from the stalk \( MN \) for a few cuts, can be calculated as follows:

\[
n = \left\lfloor \frac{1}{[((H \sin \phi - \eta) / l_{c}) + 2]}, \right\rfloor, \quad \text{if } H \sin \phi > \eta
\]

Let \( \xi \) be the Cartesian coordinate system \( O \xi \) in the feed flow, where the axis \( O \xi \) is tied with a sheabar. It was supposed, that the blade of a knife was the direct line and each blade took position on the axis \( O \xi \) periodically.

The stalk \( MN \) in the feed flow was considered at those moments when the blade takes position on the axis \( O \xi \) and the feed flow was pressed. When the front point \( M \) takes place in a housing of a cylinder or a flywheel cutterhead, the position of the stalk \( MN \) can be defined by the coordinates \( \xi, \eta \) of the point \( M \) and the angle \( \varphi \) between the axis \( O \xi \) and the cut \( MN \). It was accepted, that the independent random variables \( \xi, \eta, \varphi \) were uniformly distributed on the intervals \([0, W_c], [0, l_c] \) and \([\varphi_1, \varphi_2]\) respectively (Polyanin and Manzhirov, 2006):

\[
0 < \xi \leq W_c \quad \text{ (1) }
\]

\[
0 < \eta \leq l_c \quad \text{ (2) }
\]

\[
\varphi_1 \leq \varphi \leq \varphi_2 \quad \text{ (3) }
\]

where values \( \varphi_1, \varphi_2 \) depend of \( \xi, \eta, \varphi \):

\[
\varphi_1 = \begin{cases} 
0, & \text{if } H \leq \xi \\
\arccos(\xi / H), & \text{if } H > \xi
\end{cases}
\]

\[
\varphi_2 = \begin{cases} 
\pi, & \text{if } H \leq W_c - \xi \\
\pi + \arccos[(W_c - \xi) / H], & \text{if } H > W_c - \xi
\end{cases}
\]

The variables \( \xi, \eta, \varphi \) can be determined on intervals of boundary conditions (Equations (1)-(3)) with any accuracy by the formulas

\[
\xi = iW_c / n_{\xi}
\]

\[
\eta = j l_c / n_{\eta}
\]

\[
\varphi = \varphi_1 + q(\varphi_2 - \varphi_1) / n_{\varphi}
\]

where \( n_{\xi}, n_{\eta}, n_{\varphi} \) – the specified integers; \( i, j, q \) – integers

\[
(1 \leq i \leq n_{\xi}; 1 \leq j \leq n_{\eta}; 1 \leq q \leq n_{\varphi}).
\]
In accordance with the law of distribution of random variables $\xi$, $\eta$, $\varphi$ the integers $i, j, q$ in the Equations (6)-(8) are equal to any integer number from 1 to $n_\xi$ from 1 to $n_\eta$, from 1 to $n_\varphi$ with the probability $1/n_\xi$, $1/n_\eta$, $1/n_\varphi$ respectively. Values $\varphi_1$, $\varphi_2$ are defined by Equations (4)-(5) and depend of $i$. When the number of cycles is equaled to product ($n_\xi n_\eta n_\varphi$), the combination of integers $i, j, q$ takes all possible values.

Let us denote the length and the mass of the part under number $u$ as $w_u, m_u$ ($u$ – integer, $1 \leq u \leq n$). Let us write out representations of variables $w_u, m_u, \varphi, \eta, l$, are given.

If $n = 1$ or $H \sin \varphi < \eta$, the plant $MN$ is not cut and the length $w_1$ and the mass $m_1$ of the lonely particle 1 are the length and the mass of whole plant:

$$w_1 = H; \quad m_1 = \frac{w_1^2}{2}$$  \hspace{1cm} (13)

If $n = 2$, the plant $MN$ is cut on two parts (particles). The lengths $w_1, w_2$ of two parts can be find geometrically (Figure 7):

$$w_1 = \frac{\eta}{\sin \varphi}; \quad w_2 = H - w_1$$  \hspace{1cm} (14)

The masses of two particles for harvester, equipped with a cutter, can be calculated by Equation (9) at $a = 1$:

$$m_2 = \frac{w_2^2}{2}; \quad m_1 = [\left(\frac{w_1 + w_2}{2}\right)^2 - w_2^2]/2$$  \hspace{1cm} (15)

When $n > 2$, the particle $MN$ is cut on $n$ new formed parts. The lengths of these parts can be determined by the next formulas:

$$w_1 = \frac{\eta}{\sin \varphi}; \quad w_j = l_j/\sin \varphi; \quad w_u = H - \sum_{u=1}^{n-1} w_u$$  \hspace{1cm} (16)

where, $j$ – integer ($2 \leq j \leq n-1$).

The masses of $n$ particles for harvester, equipped with a cutter, can be calculated by Equation (9) at $a = 1$:

$$m_k = \left[(\sum_{p=1}^{n} w_p)^2 - (\sum_{p=k+1}^{n} w_p)^2\right]/2$$  \hspace{1cm} (17)

where, $1 \leq k \leq n$.

### 2.4 Value $m_L$ calculation algorithm

1. Assignment of values of variables $W_c$, $H$, $l_c$, $L$ and initial values $M_L, M_T$ ($M_L = 0$, $M_T = 0$).

2. Assignment of constants $n_\xi$, $n_\eta$, $n_\varphi$ and the variable $i$ as $i = 1$.

3. Calculations of the value $\xi$ by Equation (6) and the values $\varphi_1, \varphi_2$ by Equations (4)-(5).

4. Assignment of the variable $j$ as $j = 1$.

5. Calculation of the value $\eta$ by the Equation (7).

6. Assignment of the variable $q$ as $q = 1$.

7. Calculations of the value $\varphi$ by the Equation (8) and the value $n$ by the Equation (12).

8. Calculation of the values $w_1, m_1$ by the Equation (13), if $n = 1$, or the values $w_1, w_2$ by the Equation (14), if $n = 2$, or the values $w_i$ for all integer $k$ in the range from 2 to $n$ by the Equation (16), if $n > 2$.

9. Calculation of the values $m_1, m_2$ by the Equation (15), if $n = 2$, or the values $m_k$ for all integer $k$ in the range from 2 to $n$ by the Equation (17), if $n > 2$.

10. Increase in the amount of the value $M_T$ by the value $m_1$, if $n = 1$, or by the values $m_1$ and $m_2$, if $n = 2$, or by the values $m_k$ for all integer $k$ in the range from 1 to $n$, if $n > 2$.

11. Increase in the amount of the value $M_L$ by $m_1$, if $w_i \leq L$ for all integer $i$ in the range from 1 to $n$.

12. Increase in the amount of the variable $q$ by 1 and repetition of the actions in the items 7, 8, 9, 10, 11, if $\varphi < \varphi_2$.

13. Increase in the amount of the variable $j$ by 1 and repetition of the actions in the items 5, 6, 7, 8, 9, 10, 11, 12, if $\eta < l_c$.

14. Increase in the amount of the variable $i$ by 1 and repetition of the actions in the items 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, if $\xi \leq W_c$.

15. Calculation of the value $m_L$ by the Equation (10).

### 3 Results and discussion

The program environment ‘Lazarus’ (Free Pascal Lazarus project, Version #: 1.8.0) was used to compute the value $m_L$ by the presented algorithm and the value $m$ by the Equation (14). The source data are placed in the Table 2.

<table>
<thead>
<tr>
<th>$W_c$, mm</th>
<th>$H$, mm</th>
<th>$l_c$, mm</th>
<th>$n_\xi$</th>
<th>$n_\eta$</th>
<th>$n_\varphi$</th>
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</thead>
<tbody>
<tr>
<td>680</td>
<td>300, 400, 600</td>
<td>7.7; 13.7</td>
<td>20</td>
<td>10</td>
<td>200</td>
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</table>

Calculations showed that percent mass $m_L$ had different properties in two intervals of argument $L$. In the first interval, where $L$ ranged from zero to theoretical cut length, the function increased slowly. In the second interval, where $L$ ranged from theoretical cut length to maximal length of particles, there was rapid increasing of the percent mass (Figure 8).

Calculations also showed that precision cut forage harvester could provide quality requirements at chopping
grass for haylage when theoretical length of cut ranged from 7 mm to 16 mm (Figure 9).

These results do not contradict the recommendation to choose the theoretical length of cut for grass ensiling from 6.3 mm to 12.7 mm (Wiersma, 2013).

It can be also seen that maximal percent mass of particles in the limits from 8 mm to 19 mm is achieved when theoretical cut length is about 8 mm.

According to the considered model open throat width of chopper unit and stalk length also affect the percent mass. Increase of stalk length or decrease of the width of an open throat allows to increase percent mass of particles in diapason from 8 mm to 19 mm by length.

4 Conclusions

1. At theoretical length of cut in the range from 7 mm to 17 mm the precision cut forage harvesters can provide recommended percent mass of particles, the lengths of which exceed 8 mm and do not exceed 19 mm, in the limits from 45% to 75%.

2. The theoretical results do not contradict the recommendation to choose the theoretical length of cut for grass ensiling between 6,3 mm and 12,7 mm.

3. The estimated maximal percent mass of particles ranging in length from 8 mm to 19 mm, is achieved when theoretical cut length is about 8 mm.

References


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