

## DESIGN OF FLAIL FOR SOIL TREATMENT

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*Keywords: Flail for soil treatment, humanitarian demining*

### 1. Introduction

Machines for humanitarian demining destroy embedded mines when treating mine suspicious areas. In relation to manual mine removal, demining machines remove risks for humans, reduce time required for demining process and demining costs. Demining machines are usually equipped with flail as working tool for soil treatment and demining. Flail system for machine soil treatment consists of drive shaft, to which flails are connected, i.e. chains with striking hammers at their end. One flail consist of one striking hammer and one chain.



**Figure 1. Flail demining system (left) and one flail (right)**

Flails on rotor are mounted along the helix path on the rotor shaft. Helix starts from the middle of the rotor towards the end on each side. Often, two helix with phase shift of 180° are set up. Basic flail dimensions are: flail diameter  $D$ , rotor width  $b$ , number of helix  $n_z$ , and number of flails/hammers  $z$ .

In order to reduce number of grasping hammers, number of helix can be increased. Good flail positioning reduces number of grasping hammers and soil treatment resistance.

Hammer's phase shift:

$$\varphi_r = \frac{360}{Z} \cdot l \quad [^\circ] \quad (1)$$

Angle of hammer in grasp:

$$\cos \varphi = \frac{(R - h)}{R} \quad (2)$$

Number of flails on one helix:

$$z = \frac{360}{\varphi_r} \quad (3)$$

Number of hammers in grasp:

$$z_m = \frac{\varphi}{\varphi_r} \quad (4)$$

Axial distance between hammers:

$$l = \frac{2d + l_u}{2} \quad [\text{mm}] \quad (5)$$

$\varphi_r$  – hammer's phase shift,  $Z$  - helix path,  $d$  – hammer diameter,  $l_u$  – distance between hammer grasps

Machine working speed and rotor rpm:

$$v = S \cdot n \quad [\text{m/s}] \quad (6)$$

$$n = \frac{v}{S} \quad [\text{s}^{-1}] \quad (7)$$

$S$  – hammer shear,  $v$  – machine speed,  $n$  – rotor rpm

## 2. Flail and soil interaction

Hammer rotates around its axis with high angular speed. Hammer strikes the soil with tangential force  $F$  at the angle  $\theta$ . Force  $F$  can be divided into two components, vertical component  $F_N$  and horizontal component  $F_H$ .

$$F_N = F \cdot \cos \theta \quad [\text{N}] \quad (8)$$

$$F_H = F \cdot \sin \theta \quad [\text{N}] \quad (9)$$

Tangential force  $F$  causes hammer penetration and compressive soil disturbance. According to second Newton's Law, follows

$$F = m \cdot a_t \quad [\text{N}] \quad (10)$$

Tangential hammer acceleration:

$$a_t = m \cdot R \cdot \varepsilon \quad [\text{m/s}^2] \quad (11)$$

$m$  – hammer weight,  $R$  – hammer's centre of gravity (CG) rotation radius around rotor's axis,  $\varepsilon$  – hammer angular acceleration

Centrifugal force:

$$F_C = \frac{m \cdot v_0^2}{R} = m \cdot R \cdot \omega^2 \quad [\text{N}] \quad (12)$$

$v_0$  – circumferential hammer speed,  $\omega$  – hammer angular speed

Flail's task is to treat the soil with certain digging depth and neutralization of AP and AT mines. Normal component of force  $F_N$  should be as high as possible in order to dig the soil and crush embedded mines. Force  $F_H$  is function of angle sinus  $\theta$ , and can be decreased, but not too much, because without this force hammer penetration into the soil could not be achieved.



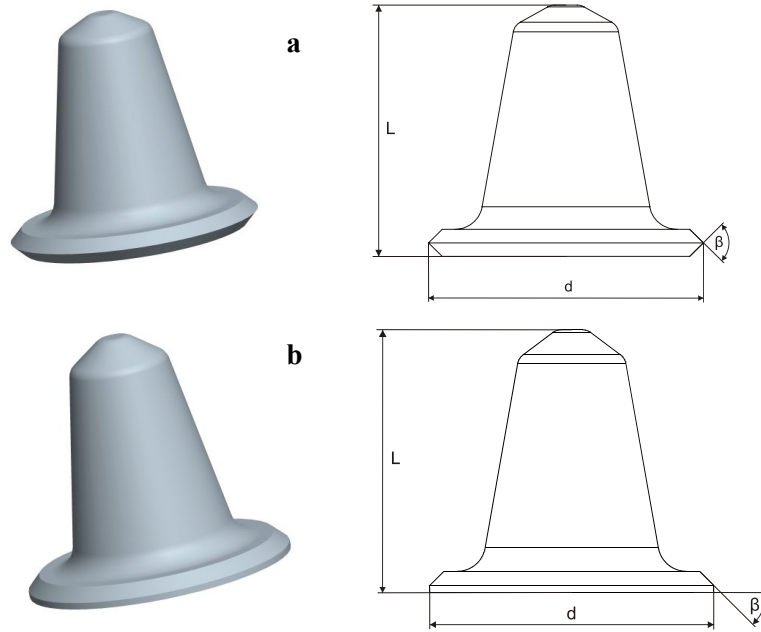
Figure 2. Cutting marks after soil treatment with flail (left); flail rotor (right)



Resultant force  $R_1$  is opposed to tangential hammer force  $F$  and represents a part of digging resistance. Stress forces  $Q$  acts vertically on wedge surface and cause friction forces  $T$ , which appear on the wedge surface. Their resultant is force  $R_2$  which represents a part of digging resistance. The wedge efficiency is determined with ratio of wedge force without friction  $R_1$  and required wedge force  $F$ :

$$\eta_{\text{wedge}} = \frac{R_1}{F} = \frac{1}{1 + \mu \cdot \text{ctg} \frac{\beta}{2}} \quad (15)$$

The wedge efficiency is higher if friction coefficient  $\mu$  is lower between the wedge and the soil, and if angle  $\beta$  is higher. For humid plastic soil, smallest digging resistance can be achieved at smaller angles, and for hard soil at higher cutting angles. This means that in this area the wedge efficiency can be observed. It can be assumed that optimal shape of striking hammer for soil treatment in all soil categories is shape of a bell or mushroom, Figure 5ab. Bell blade vertical cross section has a shape of wedge, and horizontal has cross section shape of a circle. This causes the smallest soil cutting resistances. Hammer's centre of gravity (CG) is placed on hammer axis approximately at  $(1/5 - 1/3) L$  from the hammer base. Hammer head diameter  $d$  is 50...60 (90) mm. Favorable hammer shape for lighter soil categories is shown at Figure 5b. Blade of such hammer has a shape of a wedge, designed so that lower part is vertical to strained chain. This wedge shape enables that necessary cutting angle  $\alpha$  can be achieved with smaller flail radius  $R$ .



**Figure 5. Optimal shapes of striking hammer, hammer diameter  $d$  and wedge angle  $\beta$**



**Figure 6. Working shapes of striking hammers**

Material, from which hammers are made, is usually steel for cementing, EN 16MnCr5. With cementing, hard surface layer is achieved, resistant to wear out, and core retain its ferrite – perlite structure, which is tough and resistant to dynamic and strike loads. Striking hammer exploitation life cycle is 40000...50000 m<sup>2</sup> of treated soil, i.e. around 50 working hours, after which they should be replaced. Hammer weight is between 0.75 to 1.5 kg, depending on soil hardness.

Flexible connection between shaft and hammer is a chain of 12...15 mm in diameter. Chain's exploitation life cycle is around 80000 m<sup>2</sup> of treated soil, i.e. around 80 working hours, after which it should be replaced. At the contact surface of the chain links, chain extreme wearing out is present, which causes its elongation during operations. Chains that are used for flails are usually made of steel used for improvement EN C45, and is heat treated and tempered and in order to achieve high tensile and yield strength, while retaining toughness and dynamic durability.

### 3.1 Flail geometry

When determining optimal rotor and flail dimension, the goal is to achieve required soil digging depth  $h$  with highest standard force  $F_H$ . From this fact, it can be concluded that based on standard striking force  $F_N$  component, an optimal rotor axis height  $h$  can be determined as a design parameter.

Rotor's height from the ground is:

$$h_r = R \cdot \sin \theta = (h + h_r) \cdot \sin \theta \quad [\text{mm}] \quad (16)$$

Flail angle under which hammer strikes the soil:

$$\sin \theta = \frac{h_r}{h + h_r} \rightarrow \theta = \arcsin \frac{h_r}{h + h_r} \quad [^\circ] \quad (17)$$

Soil treatment depth  $h$  is usually known and is 10...20 cm. When calculating dependence of certain flail parameters, soil digging depth  $h = 0...30$  cm and rotor radius  $R = 400...1000$  mm were simulated. Diagram of flail parameters is shown on Figure 7.

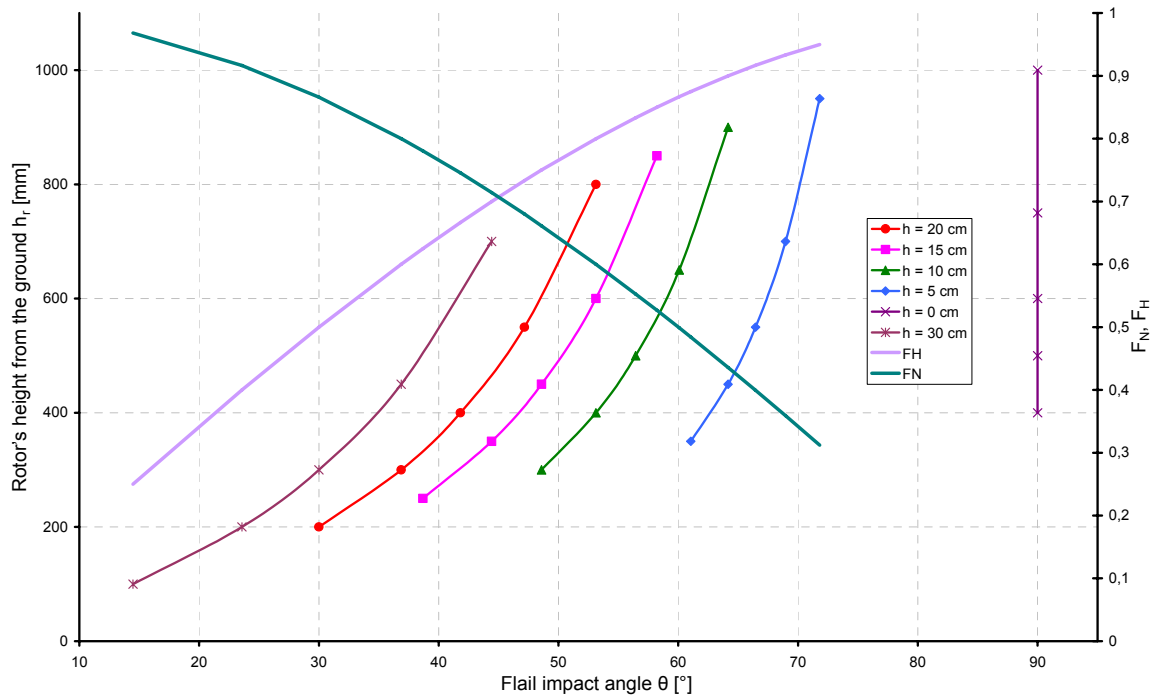


Figure 7. Flail parameters for striking hammer

If rotor height  $h_r$  increases, flail angle at which hammer strikes the soil  $\theta$  increases too. Since angle of hammer pin  $\beta$  is chosen according to soil hardness, than according to Figure. 3.:

Angle of soil cutting:

$$\alpha = \beta + \gamma \quad [^\circ] \quad (18)$$



Back pin angle:

$$\gamma = 90^\circ - \frac{\beta}{2} - \theta \quad [^\circ] \quad (19)$$

When digging resistance increases, rotor height  $h_r$  should be increased too, which further increases striking force for the same hammer angular speed. Dependence between flail angle  $\theta$  and angle under which hammer strikes the soil  $\alpha$  can be noticed. This dependence determines if the soil is treated by cutting or crushing. For determined pin angle (e.g.  $\beta = 20^\circ \dots 40^\circ$ ) dependence between flail angle  $\theta$  and cutting angle  $\alpha$  is linear, e.g.:

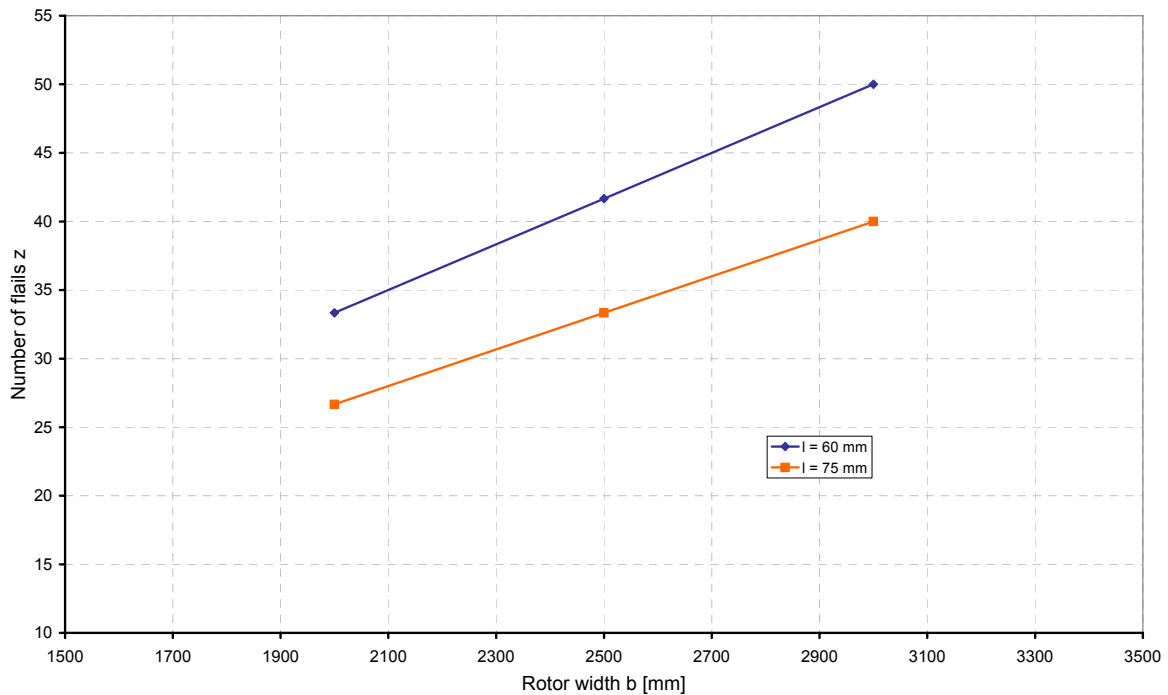
For wedge angle  $\beta = 20^\circ$ , flail angle is  $\theta = 70^\circ$ , and cutting angle is  $\alpha = 35^\circ$

For wedge angle  $\beta = 30^\circ$ , flail angle is  $\theta = 60^\circ$ , and cutting angle is  $\alpha = 45^\circ$

### 3.2 Rotor width and quantity of helixes and flails

Rotor should be designed in a way that number of hammers in grasping operation is the minimum number of hammers, because digging resistance is the lowest, and required engine power is lower, which results in lower fuel consumption and higher efficiency. Number of grasping hammers depends on rotor radius  $R$ , and digging depth  $h$ . Axial hammer distance is determined by soil treatment density requirements and is usually  $l = 0 \dots 15$  mm. If hammer distance is equal to zero, than there is no difference between the strikes in transverse direction, and if distance is e.g. 15 mm, than distance between strikes in transversal direction is 15 mm. This is acceptable, because the length of mine fuse that is to be crushed is 16 mm, and radius of the smallest AP mine (PMA-2) is 68 mm. Increase of axial hammer distance causes decrease of number of grasping hammers, as well as digging resistance.

Calculated values of hammer blades in grasp  $\varphi$ , hammer phase shifts  $\varphi_r$ , number of grasping hammers  $z_m$  and required quantity of flails/hammers  $z$  on one helix for different rotor width  $b = 2000 \dots 3000$  mm, number of helixes on rotor  $n_z = 1 \dots 3$ , axial flail distance  $l = 60 \dots 75$ , axial striking hammer distance  $l_u = 0 \dots 15$  mm, hammer diameter  $d = 60$  mm and digging depth  $h = 100 \dots 200$  mm, were simulated too.



**Figure 8. Number of flails/hammers  $z$  in function of rotor width  $b$  and distance on the rotor  $l$**

If rotor width increases, total number of rotor flails increases too. If axial flail distance on rotor is higher, number of flails decreases. Rotor width is important parameter from the machine efficiency point of view, because machine with wider rotor can treat the soil faster. Rotor width is

constant, and digging depth depends on users' requirements, flail optimization is done by selecting the number of helixes and rotor radius. At the end of analysis and flail dimensions calculation, **optimal flail parameters** can be estimated:

For soil digging depth of 20 cm and flail width up to 2 m, flail radius is between 0.75...2 m. According to this parameter, necessary flail striking force or impulse force, which enables soil cutting, can be determined. Number of striking hammers is 25...40 for the rotor width of up to 2 m, and they can be placed on two or more helixes. Striking hammer weight, regarding its volume, is 0.6 to 1.5 kg. Based on analytical calculation and machine design, it can be concluded that considered flail calculation model is adequate. Optimal values of flail parameters regarding soil treatment criteria and AT mine detonations are provided in Table 1.

**Table 1. Optimal values for flail parameters**

| <b>Rotor width <math>b</math></b> | <b>2000 mm</b>               | <b>2500 mm</b>               | <b>3000 mm</b>               |
|-----------------------------------|------------------------------|------------------------------|------------------------------|
| Rotor radius $R$                  | 400...1000 mm                | 400...1000 mm                | 400...1000 mm                |
| Digging depth $h$                 | do 200 mm                    | do 200 mm                    | do 300 mm                    |
| Number of hammers $z$             | 33 (27)                      | 42 (33)                      | 50 (40)                      |
| Hammer weight                     | 0.6 do 1.5 kg                | 0.6 do 1.5 kg                | 0.6 do 1.5 kg                |
| Hammer diameter $d$               | 60 mm                        | 60 mm                        | 60 mm                        |
| Number of helix $n_z$             | 1...3                        | 1...3                        | 1...3                        |
| Distance between strikes $l_u$    | 0 mm (15 mm)                 | 0 mm (15 mm)                 | 0 mm (15 mm)                 |
| Rotor rpm $n$                     | 300...1000 min <sup>-1</sup> | 300...1000 min <sup>-1</sup> | 300...1000 min <sup>-1</sup> |
| Working speed $v$                 | 0.5...1.7 km/h               | 0.5...1.7 km/h               | 0.5...1.7 km/h               |

#### 4. Flail testing

Calculation results were verified on development and testing of two demining machines, light 5 t MV-4 demining machine and medium 14 t RMKA-02 demining machine. Machine technical data are provided in Table 2.



**Figure 9. Demining machines MV-4 and RM-KA-02**

**Table 2. Machine parameters for soil treatment using flails: MV-4 and RMKA-02**

|                                       | <b>MV-4</b>                  | <b>RM-KA-02</b>              |
|---------------------------------------|------------------------------|------------------------------|
| Rotor width $b$                       | 1800 mm                      | 2000 mm                      |
| Rotor radius $R$                      | 450 mm                       | 450 mm                       |
| Digging depth $h$                     | 200 mm                       | do 300 mm                    |
| Number of hammers $z$                 | 27 (34)                      | 36                           |
| Hammer shape and weight $m$           | Bell-shaped hammer, 0.8 kg   | Bell-shaped hammer, 1.0 kg   |
| Hammer diameter $d$                   | 95 mm (60 mm)                | 65 mm                        |
| Number of helixes $n_z$               | 3 (2)                        | 2                            |
| Distance between hammer strikes $l_u$ | - 48 mm (- 34.5 mm)          | - 6.5 mm                     |
| Rotor rpm $n$                         | do 900 min <sup>-1</sup>     | do 600 min <sup>-1</sup>     |
| Working speed $v$                     | 0.5...2 km/h                 | 0.3...0.9 km/h               |
| Efficiency $U$                        | 500...2000 m <sup>2</sup> /h | 500...2000 m <sup>2</sup> /h |

## Conclusion

Based on analytical model of flail calculation and gained results, the following can be concluded:

1. Design of flail system is done based on soil category that will be treated using machines and requirements for digging depth  $h$  and resistance to detonation of AT mines. If treated soil is of lighter category, than rotor radius can be smaller. If treated soil is of heavier category, than rotor radius has to be bigger in order to provide adequate striking force  $F$  to overcome digging resistance.
2. Wedge angle  $\beta$  is selected according to soil category that has to be treated, and for lighter soils that are treated by cutting, a smaller angle  $\beta$  is selected, while for harder soils that are treated by crushing, a higher wedge angle  $\beta$  is selected. Additionally, for treatment of lighter soils, hammer of light weight are used, and for soils of harder categories hammers of heavier weight are used.
3. Rotor width depends on users requirements for machine working efficiency. If rotor is wider, working efficiency  $U$  is higher. Number of flails with hammers for soil digging is  $z = 25 \dots 30$  for digging width of  $b = 2$  m. Soil treatment density depends on machine movement speed  $v$  and rotor rpm  $n$ , i.e. on longitudinal distance of striking hammers  $l_u$  and distance between the hammer strikes. Optimal flail diameter is within  $D = 1 \dots 2$  m for digging of all soil categories at depth down to  $h = 30$  cm.
4. Based on testing of real machines, adequacy of calculation model and design of flails for soil treatment and demining can be evaluated.

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