Kinematic Modelling of Contact Point between Chain Bush and Sprocket

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Abstract. As is well known, in the automotive industry there is a tendency to obtain the most efficient, reliable and compact systems. Because the belt drives used are subject to excessive elongation and wear in most applications, since high performance engines are desired, distribution chains are preferred. The dynamic behavior of a chain drive during operation is directly influenced by its geometry and, implicitly, by the chain contact with the sprocket. Since the application of normal and transverse forces occurring in a chain transmission depends directly on their application point and thus on the point of contact between the chain and the sprocket, the kinematic modeling of the point of contact between the chain bushings and the sprocket is proposed in present paper.

1. Introduction

Chain transmissions used in the automotive industry must be efficient, reliable and compact. Along with these requirements, they also have the following advantages: they are capable of transmitting a wide range of speeds and powers with a negligible range; have a long lifetime due to oil lubrication and chain-to-chain contacting through the bushings (making rolling friction); can operate in hostile environments (oily areas or high temperatures). In spite of these advantages, because of the differences in the profiles of the sprockets, the dynamic behavior is treated with enough reluctance in the literature. The optimization of the chain tooth profile in the design [1] influences directly its geometry, respecting the contact surfaces that can influence the wear of the contacts between the chain bush and the sprocket [2]. A graphical analysis of the contact between the bush and the sprocket is compared for two types of profiles in [3], and in [4] a method of modeling the contact between them, based on the use of geometric parameters characteristic of a contact sprocket - chain bush [5]. In the paper [6] there is presented a kinematic model of chain link displacement according to the angle of rotation of the wheel, a model continued with variation of the specific chain elongation according to the number of teeth in contact [7]. Following these steps, it becomes necessary the modeling of the contact point between the chain bush and the sprocket.

An optimized transmission structure, engine speed and dynamic forces (such as normal and transverse forces or friction forces) can have a significant effect on its optimal functioning. Depending on the shape of the sprocket teeth and the number of teeth in the chain-wheel contact, the chain transmission forces are differentially distributed. These contact forces can be determined on the basis of the power balance between the chain and the sprocket and are directly dependent on the contact angle variation.

Knowing the variations in the contact angle and the point of contact (the point of application of the
forces in the transmission) allow optimization of the design of the transmission; therefore in this paper it is proposed a calculation model for determining the geometric position of the contact point between the sleeve and the sprocket.

Then, the model presented is applied to a case study and the results are validated with graphical representations.

2. Problem formulation

The proposed mathematical model for determining the contact point is based on the determination of the contact angle, presented in [8], for a chain transmission with a unitary transmission ratio. The considered transmission is a standardized one [9], being a short-bush chain, known for the number of sprocket teeth and geometric elements of the transmission. Based on these parameters, will result the contact angle (αi) and then the contact point coordinates (x and y). For verification, another method is used to determine the coordinates of the contact point, on the basis of which the angle of contact is determined. These values are then compared with corresponding graphical or tabular representations.

In the case study, knowing the chain pitch (p), the diameter of the chain bush (db) and the number of teeth (z), the mathematical model allows the parameters of the bushed chain transmission and the numerical values of the contact point coordinates (xi, yi) and also the contact angle (αi).

3. Determining the contact point and contact angle

3.1. Method I

This first method consists in determining the contact angle (αi) for a number of contacts (i) between the chain bush and the sprocket. Based on this, the contact point coordinates (xi and yi) are calculated for the same number of contacts.

The mathematical model for calculating the contact angle is based on the mounting position (see Figure 1), where tangential forces are assumed to be zero, and also that, for i = 0 result the first contact between the chain bush, and, the wheel position is vertical, where the notations considered to be with index 0 and α0 = 0°.

![Figure 1](image)

**Figure 1.** Geometric parameters for a chain-wheel ensemble (a) [8], with details of first four contacts (b).

For a general case of chain-wheel ensemble, is considering i = 0, 1, 2..., respectively j = i+1, the relation for determining the curves center position for sprocket (Ai, Ai) and also for chain-bush center
(B_i, B_j) can be determined:

\[ A_i B_i = r_A - r_B, \quad A_i A_j = 2R_A \sin \left( \frac{\tau}{2} \right), \quad OA_i = R_A, \quad B_i B_j = l = p + x, \quad \text{where} \; x = 0.2\% \; \text{from} \; p. \quad (1) \]

for \( i = 0 \) (mounting position) result \( \alpha_0 = 0, \; \delta_0 = 90 - \frac{\tau}{2} \), respectively \( OB_0 = R_A - r_A + r_B \).

The contact angle \( (\alpha_i) \) can be determined using the Figure 2, where the generalised Pithagora theorem is applied.

![Figure 2.](image)

**Figure 2.** The parameters for successive contact points, \( i \) and \( j \), between the chain bush and sprocket

The general algorithm [8] for contact angle calculus, result as follows:

from \( \Delta A_i A_j B_i \)

\[
A_j B_j^2 = A_i B_i^2 + A_i A_j^2 - 2A_i B_i \cdot A_i A_j \cos \delta_i
\]

\[
A_j B_j^2 = (r_A - r_B)^2 + 2R_A \sin \left( \frac{\tau}{2} \right)^2 - 4R_A (r_A - r_B) \sin \left( \frac{\tau}{2} \right) \cos \delta_i
\]

\[ \delta_i = \delta_0 - \alpha_i; \]

(2)

from \( \Delta A_j B_i B_j \)

\[ \cos \beta_i = \frac{B_i B_j^2 + A_i B_i^2 - A_i B_j^2}{2B_i B_j \cdot A_i B_i} \]

\[ \beta_i = \arccos \left( \frac{B_i B_j^2 + A_i B_i^2 - A_i B_j^2}{2B_i B_j \cdot A_i B_i} \right); \]

(3)

from \( \Delta OB_i A_j \)

\[ \cos(\gamma_i + \beta_i) = \frac{OB_i^2 + A_i B_i^2 - OA_i^2}{2OB_i \cdot A_i B_i} \]
\[
\gamma_i = \arccos \left( \frac{OB_i^2 + A_jB_i^2 - OA_i^2}{2OB_i \cdot A_jB_i} \right) - \beta_i : \\
\]

from \( \Delta OB_iB_j \)

\[
OB_j^2 = B_iB_j^2 + OB_i^2 - 2B_iB_j \cdot OB_i \cos \gamma_i ;
\]

from \( \Delta OA_iB_j \)

\[
\cos \alpha_j = \frac{OA_j^2 + A_iB_j^2 - OB_j^2}{2OA_j \cdot A_iB_j} ;
\]

\[
\alpha_j = \arccos \left( \frac{OA_j^2 + A_iB_j^2 - OB_j^2}{2OA_j \cdot A_iB_j} \right) .
\]

The contact angle led to the contact point coordinates. For a known teeth number of sprocket, \( z \), and the wheel angular pitch \( \tau = \frac{360}{z} \), result the contact points coordinates \( (x_{cj}, y_{cj}) \).

Taking account by Figure 2 and relation \( \theta_j = \theta_i + \tau \), result

\[
\begin{bmatrix}
  x_jC_j \\
  y_jC_j 
\end{bmatrix} = \begin{bmatrix}
    R_A - r_A \cos \alpha_j \\
    r_A \sin \alpha_j 
\end{bmatrix} \text{ and } T_{xy} = \begin{bmatrix}
    \cos \theta_j - \sin \theta_j \\
    \sin \theta_j & \cos \theta_j 
\end{bmatrix} .
\]

The contact point coordinates \( x_{cj} \) și \( y_{cj} \) result as relation

\[
\begin{bmatrix}
  x_{Cj} \\
  y_{Cj} 
\end{bmatrix} = T \begin{bmatrix}
  x_jC_j \\
  y_jC_j 
\end{bmatrix} = \begin{bmatrix}
    (R_A - r_A \cos \alpha_j) \cos \theta_j - r_A \sin \alpha_j \sin \theta_j \\
    (R_A - r_A \cos \alpha_j) \sin \theta_j + r_A \sin \alpha_j \cos \theta_j 
\end{bmatrix} .
\]

By transforming \( x_jy_j \) in \( xy(T_{xy}x_{ijy}) \) result

\[
T_{xy}x_{ijy} = \begin{bmatrix}
    \cos(\theta_i + \tau) - \sin(\theta_i + \tau) \\
    \sin(\theta_i + \tau) & \cos(\theta_i + \tau) 
\end{bmatrix} .
\]

Also, the relation (6) and (7) led to

\[
\begin{bmatrix}
  x_{Cj} \\
  y_{Cj} 
\end{bmatrix} = \begin{bmatrix}
    (R_A - r_A \cos \alpha_j) \cos(\theta_i + \tau) - r_A \sin \alpha_j \sin(\theta_i + \tau) \\
    (R_A - r_A \cos \alpha_j) \sin(\theta_i + \tau) + r_A \sin \alpha_j \cos(\theta_i + \tau) 
\end{bmatrix} .
\]

The previous mathematical model is applied to a real case and led to results presented in Table 1.

3.2. Method II

The previous mathematical model for determining the contact angle \( (\alpha) \) and also the contact points coordinates \( (x_{cj}, y_{cj}) \), can be verified using the second method.

In Figure 3, the chain link and sprocket ensemble is considered rotated counter clockwise with angle \( \theta^\circ \) relative to the mounting position; so, the first position is for \( A_0B_0C_0 \) and \( \alpha_0 \) when the angle \( \theta^\circ \) is imposed.
Following the Figure 3, the center coordinates for curve radius \((A_0, A_1)\) and bush center \((B_0, B_1)\) can be written as

\[
A_0 : \begin{cases} 
 x_{A0} = R_A \cos \theta \\
 y_{A0} = R_A \sin \theta 
\end{cases} \quad B_0 : \begin{cases} 
 x_{B0} = (R_A - r_A + r_B) \cos \theta \\
 y_{B0} = (R_A - r_A + r_B) \sin \theta 
\end{cases},
\]

\[
A_1 : \begin{cases} 
 x_{A1} = R_A \cos (\theta + \tau) \\
 y_{A1} = R_A \sin (\theta + \tau) 
\end{cases} \quad B_1 : \begin{cases} 
 x_{B1} = x_{B0} - l \cos \varphi_1 \\
 y_{B1} = y_{B0} + l \sin \varphi_1 
\end{cases}.
\]

Using the right line equation \(\Delta_1\) for point \(C_1\) result

\[
-\frac{x_{C1} - x_{A1}}{y_{C1} - y_{A1}} = -\frac{x_{B1} - x_{A1}}{y_{B1} - y_{A1}}.
\]

Using the circle equations for radius \(r_A\) and \(r_B\), for point \(C_1\), result

\[
(x_{C1} - x_{A1})^2 + (y_{C1} - y_{A1})^2 = r_A^2,
\]

\[
(x_{C1} - x_{B1})^2 + (y_{C1} - y_{B1})^2 = r_B^2.
\]

Also, from relation (13) and (14) result

\[
(\frac{x_{C1} - x_{B1}}{2}) (2x_{C1} - x_{A1} - x_{B1}) + (\frac{y_{C1} - y_{A1}}{2}) (2y_{C1} - y_{A1} - y_{B1}) = r_B^2 - r_A^2.
\]

Taking account by relation (12), result the coordinates \(x_{C1}\) and \(y_{C1}\)

\[
x_{C1} = x_{A1} + (y_{C1} - y_{A1}) \frac{x_{B1} - x_{A1}}{y_{B1} - y_{A1}}.
\]

Figure 3. Contact points and angles \((C_0, \alpha_0 = 0 \leq C_1, \alpha_1)\) for first two contacts, 0 and 1.
\[ y_{ci} = \frac{(y_{ai} - y_{bi})[(x_{ai}^2 - x_{bi}^2) + (y_{ai}^2 - y_{bi}^2)]}{2[(x_{ai} - x_{bi})^2 + (y_{ai} - y_{bi})^2]} + \frac{2y_{ai}(x_{ai} - x_{bi})^2 - (r_A^2 - r_B^2)(y_{ai} - y_{bi}) - 2x_{ai}(x_{ai} - x_{bi})(y_{ai} - y_{bi})}{2[(x_{ai} - x_{bi})^2 + (y_{ai} - y_{bi})^2]}, \] (17)

Replacing the relations (16) and (17) in (13), and considering it equal by zero, result the numeric value for angle \( \varphi_1 \)

\[ F(\varphi) = (x_{ci} - x_{ai})^2 + (y_{ci} - y_{ai})^2 - r_A^2 = 0. \] (18)

For contact 2 coordinates, for the centers \( A_2 \) and \( B_2 \), result \( x_{c2} \) and \( y_{c2} \)

\[ A_2: \begin{cases} x_{a2} = R_A \cos(\theta + 2\tau) \\ y_{a2} = R_A \sin(\theta + 2\tau) \end{cases}, B_2: \begin{cases} x_{b2} = x_{b1} - l \cos \varphi_2 \\ y_{b2} = y_{b1} + l \sin \varphi_2 \end{cases}, \] (19)

\[ y_{c2} = \frac{(y_{a2} - y_{b2})[(x_{a2}^2 - x_{b2}^2) + (y_{a2}^2 - y_{b2}^2)]}{2[(x_{a2} - x_{b2})^2 + (y_{a2} - y_{b2})^2]} + \frac{2y_{a2}(x_{a2} - x_{b2})^2 - (r_A^2 - r_B^2)(y_{a2} - y_{b2}) - 2x_{a2}(x_{a2} - x_{b2})(y_{a2} - y_{b2})}{2[(x_{a2} - x_{b2})^2 + (y_{a2} - y_{b2})^2]}, \] (20)

\[ x_{c2} = x_{a2} + (y_{c2} - y_{a2})x_{b2} - x_{a2}, \] (21)

Similar as for contact 1, from relation (22) result the angle \( \varphi_2 \):

\[ F(\varphi) = (x_{c2} - x_{a2})^2 + (y_{c2} - y_{a2})^2 - r_A^2 = 0. \] (22)

Generalizing for a plane circle, from relation (13) result the following relation for the angle \( \varphi_i \), which led to the point coordinates \( B_i \) and \( C_i \)

\[ F(\varphi) = (x_{ci} - x_{ai})^2 + (y_{ci} - y_{ai})^2 - r_A^2 = 0, \] (23)

where

\[ A_i: \begin{cases} x_{ai} = R_A \cos(\theta + \tau) \\ y_{ai} = R_A \sin(\theta + \tau) \end{cases}, B_i: \begin{cases} x_{bi} = x_{bi-1} - l \cos \varphi_i \\ y_{bi} = y_{bi-1} + l \sin \varphi_i \end{cases}, \] (24)

and

\[ y_{ci} = \frac{(y_{ai} - y_{bi})[(x_{ai}^2 - x_{bi}^2) + (y_{ai}^2 - y_{bi}^2)]}{2[(x_{ai} - x_{bi})^2 + (y_{ai} - y_{bi})^2]} + \frac{2y_{ai}(x_{ai} - x_{bi})^2 - (r_A^2 - r_B^2)(y_{ai} - y_{bi}) - 2x_{ai}(x_{ai} - x_{bi})(y_{ai} - y_{bi})}{2[(x_{ai} - x_{bi})^2 + (y_{ai} - y_{bi})^2]}, \] (25)

\[ x_{ci} = x_{ai} + (y_{ci} - y_{ai})x_{bi} - x_{ai}, \] (26)

Using the sprocket tooth number (\( z \)) the angle \( \theta_{\text{max}} \) can be calculated. This angle can be equal with the angular pitch (\( \tau \)). Also, depending by this angle, the angle \( \varphi_i \) for \( F(\varphi) = 0 \) can be represented.

For determining the angle (\( \alpha_i \)) between the right line \( \Delta_i (A_iC_i) \) and \( A_iO \) the scalar multiplying is used

\[ \cos \alpha_i = \frac{e_{A_iC_i} - e_{A_iO}}{\frac{A_iC_i}{|A_iC_i|} \frac{A_iO}{|A_iO|}} = \frac{A_iC_i}{|A_iC_i|} \frac{A_iO}{|A_iO|}, \] (27)
\[
\cos \alpha_i = \frac{(x_{ci} - x_{ai})(x_o - x_{ai}) + (y_{ci} - y_{ai})(y_o - y_{ai})}{\sqrt{(x_{ci} - x_{ai})^2 + (y_{ci} - y_{ai})^2} \cdot \sqrt{(x_o - x_{ai})^2 + (y_o - y_{ai})^2}}.
\]

(28)

4. Case Study

For considered chain teeth number (z), bush diameter (d_b) and chain pitch (p), the contact points coordinates between the chain bush and sprocket, which from a short-bush chain transmission, will be determined. So, for a standardized chain transmission with unitary ratio, are considered the teeth number z=16, the bush diameter d_b=5.08 [mm] and also the chain pitch p= 9.525 [mm].

The transmission parameters (Figure 1a) result as follow [7]:

\[
D_d = \frac{p}{\sin \frac{z}{180}} = 48.82 \text{ mm}
\]
\[
D_f = D_d - d_b = 43.74 \text{ mm}
\]
\[
R_{imax} = 0.505 \cdot d_b + 0.069 \frac{d_b}{3} = 2.68 \text{ mm}
\]
\[
R_A = \frac{D_f}{2} + R_{imax} = 24.55 \text{ mm}
\]
\[
r_A = R_{imax} = 2.68 \text{ mm}
\]
\[
r_B = \frac{d_b}{2} = 2.54 \text{ mm}.
\]

With the previous parameters and the first method presented, there are determined the contact angle (\(\alpha\)) depending by the contact number (i) between the chain bush and sprocket. For contact angle known values (Figure 2), the contact points coordinates (x_{ci}, y_{ci}) can be determined, when the sprocket is rotating from 0 to the angular pitch (\(\theta \in [0, \pi]\)). In table 1 the different values of coordinates x_{ci}, y_{ci} (i=0...2) and \(\alpha_i\) (i=0...2), depending by rotation angle \(\theta\) values, are presented.

**Table 1.** Contact point (x_{i}, y_{i}) and contact angle (\(\alpha_i\)) values depending by rotation angle (\(\theta\)), according to the first method.

| \(\theta\) [deg] | x_{c0} [mm] | y_{c0} [mm] | x_{c1} [mm] | y_{c1} [mm] | x_{c2} [mm] | y_{c2} [mm] | \(\alpha_0\) [deg] | \(\alpha_1\) [deg] | \(\alpha_2\) [deg] |
|------------------|-------------|-------------|-------------|-------------|-------------|-------------|-----------------|-----------------|-----------------|
| 0                | 21.87       | 0           | 20.21       | 8.37        | 15.47       | 15.47       | 0               | 7.65            | 15.03           |
| 4.5              | 21.8        | 1.72        | 19.35       | 9.93        | 14.37       | 16.45       | 1.67            | 9.36            | 16.39           |
| 9                | 21.6        | 3.42        | 18.58       | 11.35       | 12.95       | 17.48       | 3.21            | 10.72           | 17.57           |
| 11.25            | 21.46       | 4.27        | 18.19       | 12.15       | 12.15       | 18.19       | 4.07            | 11.49           | 18.33           |
| 13.5             | 21.27       | 5.11        | 17.65       | 13.06       | 11.48       | 18.82       | 4.77            | 12.33           | 18.97           |
| 18               | 20.8        | 6.79        | 16.52       | 14.39       | 10.06       | 19.89       | 6.28            | 13.77           | 20.27           |
| 22.5             | 20.21       | 8.37        | 15.47       | 15.47       | 8.87        | 20.91       | 7.65            | 15.03           | 21.9            |

Applying the second method, for known geometrical parameters and wheel rotation angle by mounting position (\(\theta_0 = 0; 4.5; 11.25; 22.5^\circ\)) and also the angle given by the precedent chain bush (\(\varphi_i\)), for \(F(\varphi) = 0\), result the contact point coordinates and also the contact angles, for the first three contacts (i=0, 1, 2). For easy comparison, in tables 1 to 5 these values (x_{ci}, y_{ci}) and (\(\alpha_i\)) are highlighted.

**Table 2.** The values for the contact angle and contact point coordinates, for \(\theta_0 = 0^\circ\), according by second method

| i=0 | x_{A0} [mm] | y_{A0} [mm] | x_{B0} [mm] | y_{B0} [mm] |
|-----|-------------|-------------|-------------|-------------|

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Based on the proposed mathematical methods and studying a real case of a chain transmission, the contact angle between chain bush and sprocket are determined. In the considered case the wheel teeth number is minimum and the transmission ratio is unitary.

According by first presented method, in Figure 4 the variation of the contact angle ($\alpha$) is presented. In Figures 5 and 6 the variation of the contact point coordinates (x and y), for different values of the sprocket rotation angle (between 0 and its angular pitch ($\tau$)) are presented.

Analyzing the Figures 4, 5 and 6 can be observed that:

- the contact angle increases linear with the increasing of the sprocket rotation angle;
- the contact point coordinates on x axis decreases with the increasing of the sprocket rotation angle; the accentuate decrease is at contacts considered in increasing order;
- the contact point coordinates on y axis increases with the increasing of the sprocket rotation angle; the accentuate increase is at contacts considered in increasing order.

### Table 3. The values for the contact angle and contact point coordinates, for $\theta_i = 4.5^\circ$, according by second method

| i  | $x_{A1}$ [mm] | $y_{A1}$ [mm] | $x_{B1}$ [mm] | $y_{B1}$ [mm] | $x_{C1}$ [mm] | $y_{C1}$ [mm] | $\varphi_1$ [deg] | $\alpha_1$ [deg] |
|----|---------------|---------------|---------------|---------------|---------------|---------------|----------------|----------------|
| i=0| 24.48         | 1.93          | 24.34         | 1.92          |
| i=1| 21.87         | 11.15         | 21.75         | 11.08         | 9.93          | 19.35         | 74.25          | 9.36           |
| i=2| 15.95         | 18.67         | 15.86         | 18.57         | 16.15         | 14.37         | 51.80          | 16.39          |

### Table 4. The values for the contact angle and contact point coordinates, for $\theta_i = 11.25^\circ$, according by second method

| i  | $x_{A1}$ [mm] | $y_{A1}$ [mm] | $x_{B1}$ [mm] | $y_{B1}$ [mm] | $x_{C1}$ [mm] | $y_{C1}$ [mm] | $\varphi_1$ [deg] | $\alpha_1$ [deg] |
|----|---------------|---------------|---------------|---------------|---------------|---------------|----------------|----------------|
| i=0| 24.08         | 4.79          | 23.94         | 4.76          |
| i=1| 20.42         | 13.64         | 20.30         | 13.56         | 12.15         | 18.19         | 67.50          | 11.49          |
| i=2| 13.64         | 20.42         | 13.56         | 20.30         | 18.19         | 12.15         | 45.00          | 18.33          |

### Table 5. The values for the contact angle and contact point coordinates, for $\theta_i = 22.5^\circ$, according by second method

| i  | $x_{A1}$ [mm] | $y_{A1}$ [mm] | $x_{B1}$ [mm] | $y_{B1}$ [mm] | $x_{C1}$ [mm] | $y_{C1}$ [mm] | $\varphi_1$ [deg] | $\alpha_1$ [deg] |
|----|---------------|---------------|---------------|---------------|---------------|---------------|----------------|----------------|
| i=0| 22.69         | 9.40          | 22.55         | 9.34          | 22.55         | 9.34          |
| i=1| 17.36         | 17.36         | 17.26         | 17.26         | 15.47         | 15.47         | 56.30          | 15.03          |
| i=2| 9.40          | 22.69         | 9.34          | 22.56         | 20.91         | 8.87          | 33.56          | 21.9           |

5. Results and Discussion
Figure 4. Contact angle variation ($\alpha_i$), depending by chain wheel rotation angle ($\theta_i$), for sprocket angular pitch ($\tau$), according by first method.

Figure 5. Contact point variation for coordinate ($x_i$), depending by the sprocket rotation angle ($\theta_i$), for sprocket angular pitch ($\tau$), according by first method.

Figure 6. Contact point variation for coordinate ($y_i$), depending by the sprocket rotation angle ($\theta_i$), for sprocket angular pitch ($\tau$), according by first method.

For results comparison, in Table 6 are presented the point coordinates and also contact angles values. It is considered that, the first contact starts from initial position on the vertical axis, $\alpha_0 = 0$, (Figure 1) and vary along the sprocket angular pitch, $\tau$ (Figure 3).
The use of such a mathematical model allows the determination of the areas of application of the transmission which contributes significantly to the optimization of such a transmission.

The correct positioning of a bush chain transmission is given, among other functional parameters, by the contact point / angle between the bushing and the sprocket, knowing that with the increase of the contact angle the friction surface between them increases.

The design of a chain drive with bushings must also take into account the contact angle or contact point, and on the other hand the load on each tooth. A larger number of contacts implies lower transmission efficiency with a lower tooth load, so a higher lifetime.

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