Application and modelling of polygon joints torque transmissions in the power transmission of electromobiles

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Abstract. The fourth industrial revolution has started, and one of its determining areas is electromobility. The author advises the exchange of the traditional torque transmission joints for polygon joints, which have proven to be more favourable. This recommendation is confirmed by many supporting facts. The parts of polygon joints can be machined with simpler and cheaper tools and target machines. The technical advantages mean economical benefits as well. This paper shows digital model equipment which assists in the graphical design of polygon joints. This tool makes the engineering and aesthetic work easier, too.

1. Introduction
The fourth industrial revolution has started, and one of its determining areas is the electromobility. Electromobility is a pillar of the 21st century. Electromobility relies on the earlier development phases of the machine and electronics industry (automatization, intelligent technologies, computers, CNC techniques, super-hard tools, novel technologies, etc.) and the results of the past hundred years of the automotive industry. The substitution of vehicles driven by environmental polluting internal combustion engines has already started. Significant results are found in both international and Hungarian studies in this area [1-3].

The relatively simple and easy to control powertrain is one of the greatest advantages of electrical driven vehicles. Because there is no need to apply complex internal combustion engines and transmissions, which are expensive to produce, this can lead to cheaper vehicle prices.

It is advisable to analyse and modernise the machine design parts of vehicles, for example: power transmission mechanisms and shaft-hub joints. This is a good time for re-evaluation of the traditional solutions. One of these issues is the expensive joints used in current designs.

2. Comparison of traditional and polygon joints
Shaft-hub joints ensure the connection between the electrical power source (motor) and the driven shaft in the power train of electromobiles. The traditional shaft-hub joints (key, taper key, rib, serrated, kerb) show many disadvantageous properties (Figure 1a). The sharp edges on these are the starting points of stress peaks, fatigue and/or shaft breakage [4-5]. This is taken into consideration by the safety factors in the strength dimensioning. The results are the following: greater shaft diameter and higher material cost. The strength dimensioning with safety factors increases the weight of the vehicle.

Furthermore, the machining is performed on more expensive, special machine tools (serrated milling machine, serrated grinding machines, broaching machines) and with expensive cutting tools with complex geometry. The traditional joints have eccentricity error.
The technical errors and the manufacturing difficulties of traditional joints are eliminated by the polygon shafts, which are non-circular, and these can be given with epicycloid and hypocycloid curves. These polygon joints can provide reliable shaft-hub connections (Figure 1b).

Polygon joints show numerous favourable properties. Among these are that stress collecting points do not form; there is no need to increase the cross-section of the shafts; their life time is higher, and they ensure self-centring [5].

The manufacturing of the polygon and cylindrical surfaces of polygon joint shafts is done in one operation by an up-to-date, target machine-like designed polygon lathe and polygon grinding machine. Furthermore, hubs with polygon bores are machined on a polygon lathe and their finishing operation is done by a small, short broaching tool. After the roughing operation, the allowance for the broaching is minimal [6-7].

Figure 1. (a) Traditional shaft-hub joint: Kerb-toothed and serrated surface (b) Polygon joints with three- and four-sided hypocycloid cross-sections

Precise accuracy can be achieved for hardened polygon bores and shaft by super hard cutting tools on polygon lathe [10], with dry machining [16] and by quasi-honing with super hard grains in fine finish (quasi honing) [11]. The hardening of the surface layer can be ensured with diamond burnishing [17-18]. The pre-machining of the torque transmission parts (shaft and hub with bore) does not change compared to the traditional technology. The production of the short broaching tool is done on a polygon lathe in roughing and on a polygon grinding machine after hardening. The manufacturing system can be assembled by target machines.

The industrial suitability of the polygon joints is justified by the polygon grinding machines manufactured by the Fortuna Works and their widespread usage [5]. The Sandvik Coromant produced the Coromant Capto fast tool-changing system (in three sizes) for machine tools with high precision and high accuracy, which apply polygon joints. These are the tools of the modern machine industry [8-9].

Development taking place in the Department of Production Engineering (nowadays: Institute of Manufacturing Science) and Department of Machine Tools (nowadays: Institute of Machine Tools and Mechatronics) of the Faculty of Mechanical Engineering and Informatics, University of Miskolc has been used e.g. in the machine industry, tool manufacturing for the mining industry, and the production of forms for glass industry [6-7]. The manufacturing of many workpiece-actuated polygon lathes and
grinding machines was carried out in the two departments. These results can provide a prospective future for the automotive industry. The novel results of this research led to the publication of many papers, dissertations and patents. The enumeration of those exceeds the extent of this paper. Polygon joints can be designed and manufactured with different tools and shapes according to the German standard [12]. The draft for a Hungarian standard has been completed [13].

3. Parametrical equations and graphical representation of polygon joints

3.1 Epi- and hypocycloids
In normal sectional view the polygon joints are epi- and hypocycloids or curves related to those. Numerous international and national polygon machining methods are known. Most of the procedures can be traced back to one base case: the generation of the cycloid. Figure 2c models the generation of polygon curves. The basis of this is the following: the epi- or hypocycloid is generated by the Point P assigned on a circle rotating around Point O₁, which rolls down without slip on the base circle rotating around Point O (which is the generating plane).

In the practice, the normal sectional view for most of the polygon joints is a stretched hypocycloid (stretching factor: \( \lambda < 1 \)). The parametrical equation of the hypocycloids with the notation of Figure 2 is:

\[
\begin{align*}
\begin{align*}
x &= x(\delta) = L_t \cos \delta + e \cos C_2 \delta \\
y &= y(\delta) = L_t \sin \delta + e \sin C_2 \delta
\end{align*}
\end{align*}
\]

where

\[
L_t = R - r ; \quad e = \lambda r \quad \text{and} \quad C_2 = \frac{R - r}{-r}
\]

R: radius of base circle; r: radius of pitch circle; \( \delta \): rolling angle; e: excentricity.

Figure 2. (a) Geometry of the hypocycloid profile (b) g-marked plane curve given by external program carrier (c) Kinematic model of profile mapping
The following equations can be written based on the geometric and kinematic relations which must be fulfilled:

\[ \omega_2 = \omega_1 \cdot \frac{R}{r} = \omega_1 \cdot N_s ; \quad N_s = \text{integer} \quad \frac{R}{r} = \text{integer} \quad \frac{\omega_2}{\omega_1} , \]

where the used notations are the radius of the base circle (R), the radius of the pitch circle (r); and their angular speed (\(\omega_1, \omega_2\)). It is a requirement that the number of the polygon sides must be an integer: \(N_s = 1, 2, 3, 4, \ldots\). If the rotation direction of the two axes is the same, a hypocycloid is generated. If these directions are the opposite, the result is an epicycloid. In the working model equipment, the adjustable parameters are: \(\omega_1, \omega_2, R, r, L_t, r, N_s, e\) (Figure 3). The kinematic mapping system (Figure 2c), which solves Equation (1) and (2) and which is based on the superposition of two rotary movements, is capable of mapping different hypocycloids, ellipses, Pascal spirals and cardioids. The criterion is that the executing unit V should operate based on Equations (1) and (2). The realisation of the g-curve in Figure 2b can be done by external data input depending on the need.

3.2 Model equipment to generate digital epi- and hypocycloids

The visual fast supervision of the designed polygon profile is necessary in the design of the polygon joint and in the adjustment of the polygon machining equipment. Therefore, the author planned and built model equipment capable of generating of digitally controlled polygon-curves for the visualisation of epi-, hypocycloids and other different curves.

The theoretical structure of the equipment is shown in Figure 2c, where there is a writing tool in the P point (which symbolises one point of the cutting edge) and the plane of registration is the x-y plane (symbolises the normal cross-section of the workpiece). The two revolving axles (with \(\omega_1\) and \(\omega_2\) angular speed) of the digital model equipment are rotated by controlled stepper motors (V in Figure 2/c), which are connected to the transmission, according to the orders of control unit I.

![Figure 3. System structure of the digital model equipment](image)

The schematic of the equipment is shown in Figure 3. The symbols are: base plate with the bearing of axle 1 (A), console with the bearing of axle 2 (K), plane of registration (S), writing tool (P), adapter...
transmissions ($HM_1$, $HM_2$), electric stepper motors ($LM_1$, $LM_2$), the distance of $P$ point from axle 2 ($e$), polygon number selector ($Ns$) and external data input ($KA$). Figure 4 shows a photograph of the graphical unit of the model equipment.

The inspection of the system is provided by the generation of a Cardano line, whose basis is: the model equipment works correctly if the registrate of two controlled, given rotary movements is a line. The controlled, correct function check of control unit I and the two stepper motors in unit V was done by this method.

The shape of the cycloid can be changed with the help of the polygon number ($Ns$) and the other adjustable parameters shown in Equations (1) and (2) (Figure 2a and 2c). There is an option for external data input for special path mapping tasks. These tasks occur for example in the machining of cam plates and decorative surfaces (Figure 2b). Recordings generated by the model equipment are shown in Figures 5-8.

In modern torque transmission polygon joints, the usage of convex or nearly linear curved hypocycloids is advisable. The two outer curves in Figure 7, which are extended hypocycloids, are good example for this. The two inner curves are peaked hypocycloids.

**Figure 4.** Graphical unit of the modelling equipment

**Figure 5.** Five-sided peaked and looped epicycloid

**Figure 6.** Six-sided peaked epi- and hypocycloid
The normal cross-sectional shape, characteristic dimensions, fit and surface quality (roughness) requirements of the polygon joints (fitted shaft-hub connections) can be determined by the German standard. The optimal strength design and check is done by the method of Mechnik furthermore Citarella and Pertella [14-15].

4. Conclusion, proposal and vision

The internal combustion engine and the needed transmission are very complex constructions from the points of view of both design and production. These are made with numerous parts, which need certified materials and blanks, special, expensive machine tools for machining, and complex tools and technologies. The service and repair of internal combustion engines are more expensive than the electric power supply of the electromobiles.

In the last century, the automotive industry settled on the traditional shaft and hub joints. It is time to change to polygon joints in the starting century of electromobility: they are better in quality, advantageous in characteristics and more economical. It has been proven that better quality parameters, easier and cheaper tooling, lower number of machining operations and target machines, smaller workspace, lower energy consumption can be achieved. Polygon joints, machining target machines and technologies are promising for the automotive industry based on the results of the research and development work so far.

The engineering tasks (analysis and design of polygon profiles, drafting of cam plates) often need fast graphical visualisation, which is helped by the digital model equipment presented in this paper. Many problems need to be answered in Hungary as well, for example the building of a suitable electrical charger network, the research and development of fast recharge and energy storage, the installation of technical bases and services, the teaching of specialists and the reduction the expenses. An electrical driven vehicle could be significantly cheaper if the costs of electrical power storage could be lowered. This is still to be expected, because lithium batteries are used nowadays. Sadly, the world market price of lithium is increasing.

Hungary can become one of the leading countries in electromobility with the application of the earlier and current novel research results. This work aims to contribute to this objective.

Motto

Henry Ford dreamed of and manufactured a car which could be bought by the workers of the Ford Industries. This was achieved! This thought must act as a model for the present-day automotive industry.
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