Extended horn gears in 3D maypole braiding: Theoretical analysis, gear arrangement and prediction of the floating length

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Abstract
This article presents the theoretical background for the arrangement of horn gears in maypole braiding machines in order to act as equivalent larger gears. The theoretical analysis is verified with numerical simulation and experiments. After review about the state of the art, an analysis of the process for one specific configuration of horn gears is given. This analysis demonstrates how a set of horn gears can be arranged to work as an equivalent to a larger one horn gear. The braiding equation is checked as remaining valid for such extended configurations, too. The theoretical result is verified using numerical simulation for all cases and practical validation for several variants. The theoretical rules give a clear extension of the current braiding knowledge and make the design of complex configurations of braiding machines more systematic and clear.

Keywords
Circular maypole braiding, floating length, equivalent composed horn gears, structure, carrier arrangement

Introduction
Maypole braiding is a process of interlacement of at least three yarns, building linear or shell-like structures used in a wide range of applications. Classical applications of braiding are producing ropes, tubes or shoe laces. In recent years, modern braiding machines find even more applications in the field of medicine, where complex forms can be produced and adjusted using the variation of paths, for instance, using the 3D braiding technique or its smaller modern solutions, the so-called ‘variation braider’. The main problem in the development of these structures is that the machine development and the carrier arrangement are done by trials and errors and the fundamental theoretical background is not well developed. This work presents a step in filling this gap – it presents the theoretical analysis of equivalent extended horn gears and its application in maypole braiding.

The results described in this work were obtained after conducting a large number of numerical experiments and were proved after that on a real machine. The simulation of the carrier motion and the visualization of the braided products for different horn gears and carrier arrangements resulted in a gain of experience and gave a better understanding of the process in a short time span. The simulation also allowed evaluation of various configurations for machines that do not exist or are not accessible to the author.

State of the art
There are a few research works which try to define relations and trials for occupation of the carrier arrangements based

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on mathematical rules.\textsuperscript{4} The theory seems promising, but from the article, it is not directly applicable. The group theory from the mathematical topology\textsuperscript{5} also has the potential to give the fundamentals for the arrangement of the maypole braiding machines, but at the current state, it is very abstract and not directly connected to the braiding applications. Büsgen\textsuperscript{6} developed an algorithm for simulation of the carrier motion of machines with a square set of horn gears with dynamic switches, and the software CABRUN (Herzog GmbH, Oldenburg, Germany)\textsuperscript{7} allows numerical trials before the machine is started. Kyosev\textsuperscript{8} proposed the method and software ‘Texmind Braiding Machine Configurator’\textsuperscript{9} for simulations of the carrier motion for any arbitrary arrangement of horn gears, not limited to square sets of four slot horn gears. The reported results\textsuperscript{10,11} demonstrate the capability of the software for performing development of braiding machine configurations based on trials and errors. Nevertheless, the development of braided profiles with complex cross sections as required for fibre-reinforced composites requires a large number of trials in order to receive useful machine configuration like those reported in the literature.\textsuperscript{12–17} For all such cases, a systematic methodology is missing. This article gives a step in the development of such theory.

**Theoretical basis**

The current theory is based on the direct relations between the product and the process. The basic equation which determines relationship between the horn gear size and the carrier arrangement was found according to the author’s record first in the book of Goseberg\textsuperscript{18} and explained with more details in the book of Kyosev.\textsuperscript{1} The equation defines the floating length $L_F$ as the whole number of the ratio between the number of slots of one horn gear $N_{\text{slots}}$ and the repeat of the carrier arrangement $R_{\text{ca}}$:

$$L_F = \left\lfloor \frac{N_{\text{slots}}}{R_{\text{ca}}} \right\rfloor$$

The repeat of the carrier arrangement $R_{\text{ca}}$ gives the smallest number of the occupied and empty slots along one track, which have the same arrangement. For regular arrangements

$$R_{\text{ca}} = N_{\text{full slots}} + N_{\text{empty slots}}$$

so that for instance carrier arrangement ‘1 Full–1 Empty’ leads to repeat of 2 slots.

Figure 1 demonstrates the principle for derivation of this equation. Let one horn gear have four slots ($N_{\text{slots}} = 4$) and in one of these is placed the carrier A. For the time of one complete revolution of the horn gear, the carrier A will travel forward along the track path, equal to the length of four ($N_{\text{slots}}$) slot arcs. This carrier (A) and its yarn will cross the path of so many carriers and their yarns, as placed in four ($N_{\text{slots}}$) slots of the opposite track. If the arrangement is 1 Full (occupied slot with carrier) and 1 Empty (not occupied slot), then the four slots will have two carriers moving two yarns. The carrier, running in the opposite direction, will interlace its own yarn with these two yarns. According to equation (1), $4/(1$ full + 1 empty) = 2 other yarns, so the floating length is two in this case.

At each place, where two tracks are intersecting, the yarns interlace (Figure 2). With four slot horn gears, the maximal floating length is two, because half slots have to be kept empty for the carriers of another track. For the braiding of sensible on bending yarns like carbon or glass or for some special effects in the structure, a larger floating

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The number of the carriers which will pass through one gear for its complete rotation and will intersect their yarns with one yarn of the opposite direction determine the floating length.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Each horn gear builds one ridge of the braided product. Contact places between the gears, where the tracks intersect, are the borders of one ridge.}
\end{figure}
length can often give some advantages. Grouping several horn gears to work in a way together so that the track does not intersect with another track (or itself), it allows extending the possibilities of normal braiding machines without the need for changing the gears.

Figure 3(a) demonstrates the principle of building an extended horn gear using four horn gears. Selecting the track so that the carrier moves on the one side through slots 1-2-3-4 and through the opposite direction through 4-5-6-7-8, the four horn gears build an extended horn gear, equivalent to a larger one with eight slots (Figure 3b). Assuming that all horn gears move with such angular velocity that their peripheral velocity remains constant, it will be important to note how many slots are available at all on its track for such an extended horn gear and not from which size the single horn gears are built. As there is no intersection of the tracks, equation (1) has to remain valid, with the notice that $N_{\text{slots}}$ in this case is the number slots of the extended horn gear:

$$L_F = \left[ \frac{N_{\text{slots}}}{R_{ca}} \right] = \left[ \frac{\Sigma L_i}{R_{ca}} \right]$$

Figure 4. Track configuration for realization of extended gears with eight slots for floating length of four.

Figure 5. Carrier occupation and switches for realization of extended gears with eight slots for floating length of four.
optically, if some of these are rotated at the specific angle. In such case, their number can be determined as a ratio between the total length of the track \( \sum L_i \) and the length of one slot \( L_{\text{slot}} \): \[
N_{\text{slots}} = \frac{\sum L_i}{L_{\text{slot}}}
\] (4)

Validation using numerical and real experiments

For validation of the theory, a configuration as shown in Figure 4 is selected. All 16 horn gears participate in the carrier motion, building four extended horn gears with 8 slots each. The structure should have four ridges and for carrier occupation of ‘1 Full–1 Empty’ floating length of \( 8/(1+1) = 4 \). The carrier occupation and the positions of the switches are visualized in Figure 5.

The simulation of the carrier motion and the idealized geometry with the TexMind Braiding Machine Configurator software produces a virtual braid with four ridges and floating length of four (Figure 6(c) and (d)) and confirms the validity of the theory. The practically realized braid with this configuration on machine VF-1-32/140 of company Herzog GmbH, Oldenburg, Germany, confirms the structure too (Figure 6 (a) and (b)).
Influence of asymmetry in gear arrangement

Figure 7 demonstrates a configuration with extended gears with 16 slots, where a well recognizable asymmetry in the arrangement is available – the inner part track has 5 slots and the outer has 11. In the braiding equation, there is no difference between symmetrical and asymmetrical arrangement for normal gears, and no difference is expected as well for extended gears. Using the carrier arrangement as demonstrated in Figure 8, the structure is simulated virtually and produced on the same machine (VF 1-32/140). The top view of the simulation in Figure 9(a) demonstrates how the carriers of one track are moving longer around and during this longer way, they cross more yarns of the opposite track, as it can be counted from the side view in Figure 9(b). The real sample in Figure 9(c) confirms the floating length of 8 of this ridge and confirms that there is no influence of the asymmetry of the gear arrangement for the floating length or the structure type respectively.

Enlargement of the extended horn gears and floating length of their ridges

If a set of extended horn gears is analysed, it can be identified and proved that each extended horn gear can be extended to a larger one if few repeating sets of horn gears and their tracks, named here extension units, are added. Figure 10b represents one such extension unit, built of three horn gears. This unit can be found as a repeating set in the configurations in Figure 10(a) and (c). It consists of four arcs each with the length of one slot, so they correspond to one ‘four slot’ gear.

Adding one such unit to the existing configuration extends the extended horn gear with four slots, or – for arrangement of ‘1 Full–1 Empty’ – with a floating length of 2. For a track built of four slot horn gears, this means that the possible extended gears would have 4, 8, 12, etc. \(N-4\) number of slots and floating lengths of 2, 4, 6, etc. \(N-2\) are possible, where \(N\) is the number of single four slot gears and extended four slot units at all. This rule can be summarized for horn gears with any number of slots \(N_{\text{slots}}\) and any carrier arrangement:

Let a set of arcs of horn gears, each with \(N_{\text{slots}} = 2i\) slots, where \(i \in \mathbb{N}\), are available and configurable, so that they can build a closed non-self-intersecting curve as a track for carriers. Let there be moving carriers along this track, with repeat of the carrier arrangement \(R_{\text{ca}} = N_{\text{full slots}} + N_{\text{empty slots}}\).

With such a configuration, extended horn gears with \(N_{\text{slots, composed}} = k \cdot N_{\text{slots}}\) slots can be built, where \(k \in \mathbb{N}\) and such an extended gear will produce ridge with floating length of

\[
L_F = \frac{k \cdot N_{\text{slots}}}{R_{\text{ca}}} = \frac{k \cdot N_{\text{slots}}}{N_{\text{full slots}} + N_{\text{empty slots}}} = k \cdot L_{F,\text{unit}} \quad (5)
\]

For this configuration adding one extension unit, which represents the smallest extension set, leads to increment of the floating length with

\[
L_{F,\text{unit}} = \frac{N_{\text{slots}}}{N_{\text{full slots}} + N_{\text{empty slots}}} \quad (6)
\]

which determines the possible floating lengths.

Floating length of the extension unit \(L_{F,\text{unit}} = 1\) will allow configuration of extended gears with any floating length \(L_F \in \{1, 2, 3, 4, 5, \ldots\}\), but practically this is seldom used. For this case, two options are possible:

- Using horn gears with two slots \(N_{\text{slots}} = 2\) and carrier arrangement 1 Full–1 Empty, according to the equation for floating length \(2/(1+1) = 1\). This case is
possible, but it leads to a machine which is not able to produce any other pattern; so in reality, such one was never built.

- Using partial occupation (1 Full–3 Empty) for the carrier arrangement. In this case for large enough machine, any floating length is possible, but it will be less efficiently used.

The most used horn gears with \( N_{\text{slot}} = 4 \) have a floating length of the extension unit \( L_{F, \text{unit}} = 2 \) and allow ridges with floating length \( L_F \in \{2, 4, 6, \ldots, 2 \cdot k\} \). Machines with \( N_{\text{slot}} = 6 \) are available too, and they will allow the production of ridges with floating lengths of \( L_F \in \{3, 6, 9, \ldots, 3 \cdot k\} \), and those with \( N_{\text{slot}} = 8 \) will allow ridges with \( L_F \in \{4, 8, 12, \ldots, 4 \cdot k\} \), respectively. For all these cases, \( k \) is natural number (\( k \in \mathbb{N} \)).

**Conclusions**

This article presents a method for building extended horn gears, which allows the production of samples with larger floating length of maypole braiding machines with smaller horn gears. It is demonstrated that the equation for the floating length of the braids remains valid as well for the case of extended horn gears and that asymmetric arrangements of the horn gears do not have influence over the floating length of the extended horn gear. The method is verified with numerical simulation of the braiding process and with real samples, produced on variational braiding machine VF 1-32/140 with \( 4 \times 4 \) set of horn gears. The described method presents a step in the creation of systematic rules for design and configuration of 3D braiding machines based on the maypole braiding principle and its understanding will reduce the time taken in trials and errors during the creation of configurations of new machines.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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