Optimizing the way kinematical feed chains with great distance between slides are chosen for CNC machine tools

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Abstract. This paper presents a new method, based on FRISCO formula, for optimizing the choice of the best control system for kinematical feed chains with great distance between slides used in computer numerical controlled machine tools. Such machines are usually, but not limited to, used for machining large and complex parts (mostly in the aviation industry) or complex casting molds. For such machine tools the kinematic feed chains are arranged in a dual-parallel drive structure that allows the mobile element to be moved by the two kinematical branches and their related control systems. Such an arrangement allows for high speed and high rigidity (a critical requirement for precision machining) during the machining process. A significant issue for such an arrangement it’s the ability of the two parallel control systems to follow the same trajectory accurately in order to address this issue it is necessary to achieve synchronous motion control for the two kinematical branches ensuring that the correct perpendicular position it's kept by the mobile element during its motion on the two slides.

1. Introduction

As a result of the growing demand for high speed precise manufacturing, computer numerical controlled machine tools with kinematical feed chains with great distance between slides have become increasingly common, examples: gantry milling machines, plasma and laser gantry cutting machines, vertical lathe machines etc [1]. Such machines are usually, but not limited to, used for machining large and complex parts (mostly in the aviation industry) or complex casting molds. In such machines at the mobile element (traverses, portals etc.) level, when we use only one drive unit, there is a tendency of the mobile element to rotate in plane. To address this problem the kinematic feed chains are arranged in a dual-parallel drive structure that allows the mobile element to be moved by the two kinematical branches and their related control systems. Such an arrangement allows for high speed and high rigidity (a critical requirement for precision machining) during the machining process. However when we use the dual-parallel drive structure we can observe a specific phenomenon where the application point of the resistive force differs from the application point of the driving force, such a difference causes a bending moment, Figure 1, to be induced in the mobile element (the mechanical coupling between the two kinematical feed chains). The resulting deformed force of the mobile element components causes the trajectory tracking error of the cutting tool to increase. As such establishing a drive solution that can synchronize accurately the kinematical feed chains for the mobile element it’s a requirement for decreasing the trajectory tracking error on computer numerical controlled machine tools with great distance between slides, especially when machining parts with complex surfaces at
high speeds. The synchronization can be made electronically and/or at the software level using a close control loop that can ensure good synchronization of the two kinematical feed chains dose keeping a correct perpendicular position on the slides during movement, regardless of torque disturbances or differences in dynamic behaviors of each control loop taken separately.

**Figure 1.** Synchronization error for the dual-parallel drive system.

1.1. Command solutions for synchronous control of the two kinematical feed chains

In order to create such a control loop, we will consider one of the two kinematical feed chains as being the master motion control axis (Master) and the other feed chain as being the slave motion control axis (Slave). We can classify the synchronous motion control strategies into four categories:

1. The synchronous parallel control of kinematical feed chains;
2. The master-slave control of kinematical feed chains;
3. The relative dynamic stiffness motion control of kinematical feed chains [2];
4. Cross-coupled control system of kinematical feed chains [3].

The control structure for case 1 is illustrated in Figure 2, its primary advantage of this control structure lies in its simplicity. However this control structure can’t guarantee accurate synchronous movement due to inevitable and nonlinear errors that occur in the mechanical systems (drive screws, mechanical couplings, etc.). In order to improve upon the above mention control structure a master-slave control structure, Figure 3, is propose for case 2, which operates in cascade allowing the slave motion control axis to follow the master motion control axis with a higher dynamical stiffness. In the master-slave control scheme the synchronization error can be eliminated only if it appears at the level of the master axis since the communication between the axes is unidirectional this does not allow the master axis to detect the asynchronous movement of the slave axis when it encounters unanticipated load disturbances also the servo-lag between the master axis and slave axis cause synchronization errors. Therefore, a new control scheme to address the shortcomings of the master-slave control system is propose in case 3, the relative dynamic stiffness motion control [2] which allows the synchronization error to be compensated by both axis. This it’s achieved by a hybrid position-velocity synchronous control. Its key feature is that the two servomotors compensate each axis in the velocity loop. the position controller is only employed on the master axis this can eliminate the servo-lag
Figure 2. The synchronous parallel control of kinematical feed chains.

Figure 3. The master-slave control of kinematical feed chains.

Figure 4. The relative dynamic stiffness motion control of kinematical feed chains [2].
Figure 5. Cross-coupled control system of kinematical feed chains [3].

error which occurs in the master-slave from caste 2. The relative dynamic stiffness motion control it’s illustrated in Figure 4. In case 4, in order to reduce the synchronization error a multi-axis motion control system based on cross-coupling controller between the master motion control axis and the slave motion control axis was propose [3]. While this method it’s suitable for dual-parallel drive systems it is comply applied to multi axis systems as its complexity makes it expensive.

2. Optimization method based on the FRISCO algorithm
The optimization method based on the FRISCO algorithm [4] represents a compromise between fine optimization method proposed by Pahl and Beitz [5] and the rough optimization method, also known as screening, based on the evaluation metrics proposed by Pugh [6]. Comparing the two methods we can highlight three phases:

1. Establishing the evaluation criteria and their coefficients weight;
2. Grading (on a convenient scale) the way each solution (conceptual variant) fulfils each of the evaluation criteria. We can then calculate weight grades as the product between the conferred grade and the afferent criterion weight coefficient;
3. All the weighted grades of each solution are summed and ordered based on the obtained sums (score).

The main difference between the two methods lies in the first phase. Solving this first phase with de Pahl and Beitz method (based on the objectives tree) it’s accurate but laborious (needs a high volume of work). Solving the first phase with the second method it’s fast and intuitive but imprecise [4]. The FRISCO algorithm its mathematical procedure for calculating weight coefficients relatively precise and fast.

2.1. Methodology for applying the FRISCO algorithm
For each of the four conceptual variants chosen (I, II, III, and IV), there can be more, and \( n=4 \) evaluation criteria: \( a > b > c > d \) (\( > \) means: more important than) we will establish the weight coefficients of the criteria a, b, c, and d after witch we can order the conceptual variants I, II, III, and IV using their value.

3. Optimizing the way command and control systems are chosen for kinematical feed chains with great distance between slides using the FRISCO method
The synchronous parallel control of kinematical feed chains represents the first conceptual variant I. The master-slave control of kinematical feed chains represents the second conceptual variant II. The
third conceptual variant III is the relative dynamic stiffness motion control of kinematical feed chains and the forth conceptual variant, IV, is the cross-coupled control system of kinematical feed chains. The evaluation criteria’s will be: (a) positioning precision, (b) reaction time, (c) cost and (d) complexity and these criteria listed in order of importance.

With the help of the $n\times n = 4\times 4$ matrix from table 1 we will establish the score $P_k$ and then place $L_k$ for each criterion $k$ ($k = 1, 2, 3, 4$). In order to operate in the matrix form table 1 we will need to observe the following rules:

1. The criterion from row $k$ ($k = 1, 2, 3, 4$) is compared to each of the given criteria getting the following grades: 0 (if it is less important than the criterion being compared to), 0.5 (if both have the same importance) and 1 (if it is more important than the criterion being compared to).

2. Establishing global score $P_k$ for the criterion from row $k$ ($k = 1, 2, 3, 4$) by summing the grades on the row.

3. Establishing the places for the $n = 4$ criteria ($L_k = 1, 2, 3, 4$), by comparing the obtained scores.

Then we will establish quantity $S_k$ that designates the number of criteria whose global grades are inferior to the global grade of the current criterion $k$. For example, we can use table 1: for criterion b (which has the score $P_k = 2.5$), there are $S_k = 2$ criteria with smaller scores (criterion c with $P_k = 1.5$ and criterion d with $P_k = 0.5$).

After the above mention steps the FRISCO algorithm can establish both the absolute values $W_k$ of the weight coefficients and their relative values $w_k$:

$$W_k = \frac{2 \cdot P_k - P_{\min} + S_k + 0.5}{0.5 \cdot n + P_{\max} - P_k}$$  \hspace{1cm} (1)

$$P_{\max} = \max(P_k, k = 1 \ldots n)$$  \hspace{1cm} (2)

$$P_{\min} = \min(P_k, k = 1 \ldots n)$$  \hspace{1cm} (3)

$$w_k = W_k \left( \sum_{1}^{n} W_k \right)^{-1}$$  \hspace{1cm} (4)

**Table 1.** Determining the relative coefficients of weight of the criteria a, b, c and d.

| $k$ | Criterion | a | b | c | d | $P_k$ | $L_k$ | $S_k$ | $W_k$ | $w_k$ |
|-----|-----------|---|---|---|---|-------|-------|-------|-------|-------|
| 1   | a         | 0.5 | 1 | 1 | 1 | 3.5   | 1     | 3     | 5     | 0.59  |
| 2   | b         | 0   | 0.5 | 1 | 1 | 2.5   | 2     | 2     | 2.33  | 0.27  |
| 3   | c         | 0   | 0  | 0.5 | 1 | 1.5   | 3     | 1     | 1     | 0.12  |
| 4   | d         | 0   | 0  | 0  | 0.5 | 0.5   | 4     | 0     | 0.2   | 0.02  |

Suma: 8.53

Based on the results from table 1 we can perform the following operations:

1. First we grade with notes $N_k$ from 1 to 0 the way in which each criterion is fulfilled by each conceptual variant (I, II, III and IV). This grading it’s based on each conceptual variants performances;

2. Then we will calculate the weighted grades, as the product between the grade $N_k$ and the afferent relative coefficient of weight $w_k$;
3. After determining \( w_k \cdot N_k \) we establish each conceptual variants score by summing up its own weighted grades;

4. Based on the establish score we can determine the best conceptual variant by comparing the score.

| Table 2. Ordering the four conceptual variants (I, II, III and IV). |
|-----------------|-----|-----|-----|-----|-----|-----|
| Criterion       | I   | II  | III | IV  |
| \( w_k \)       |     |     |     |     |
| \( N_k \)       |     |     |     |     |
| \( w_k \cdot N_k \) |     |     |     |     |
| \( N_k \)       |     |     |     |     |
| \( w_k \cdot N_k \) |     |     |     |     |
| \( N_k \)       |     |     |     |     |

| | I | II | III | IV |
|---|---|---|----|----|
| a | 0.59 | 5 | 2.95 | 6 |
| b | 0.27 | 8 | 2.16 | 7 |
| c | 0.12 | 9 | 1.08 | 8 |
| d | 0.02 | 10 | 0.2 | 9 |

| Sum: | 31 | 6.39 | 30 | 6.57 | 30 | 8.11 | 25 | 8.02 |
| Place: | 4 | 1 | 3 | 1 | 2 |

4. Conclusions
As we can observe the FRISCO algorithm can be applied directly and effectively even when there are a large number of solutions (conceptual variants), this allows for a significant reduction in work time while not losing as much precision compared to rough evaluation methods. As for the conceptual variants presented in this paper we can affirm that the variant III (The relative dynamic stiffness motion control of kinematical feed chains) gets the best score mainly due to its simplicity and lower price while not sacrificing precision.

5. References
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