EXPERT SYSTEMS – COMPUTATER AIDED DETERMINATION OF TEETH NUMBER OF MACHINE TOOL GEARBOXES

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Abstract. An expert system has been created to aid mechanical engineers design and choose the suitable gearbox teeth number using spur gears and diminish the time expended on machine design. The expert computational system for evaluation of the gearbox teeth number was made and tested. The tests shown that the algorithm used in this system makes easy, fast and safe to find the most suitable relation of size and cost for a given transmission, allowing several analyses of many others distinct configurations. There is more an important option to generate a printed design report and several speed charts.

Keywords: Expert Systems, Speed Variator, Machine Design, Gearbox.

1. INTRODUCTION

An expert system is a computer program that contains the knowledge and analytical skills of one or more human aspects to aid the designer job. It is made up of two distinct parts: (1) a set of rules that analyze information, usually supplied by the user of the system, about a specific class of problems and (2) an inference rule, that links these rules and gives to the expert systems the ability to find solutions, errors diagnose and, ideally, to recommend an action in order to implement corrections.

According to NBR 13766/1997 standard [2], speed variators are defined as speed-power convesors. They are transmission devices that changes torque and speed according to the needs.. These equipaments are extensive used in machine tools and automotive vehicles. Figure 1 (a), (b) and (c) shows different types of speed variators. Since the Industrial Revolution several types of machines and tools have being developed in order to execute the most diverse tasks. However, it was only during the XIX century, with the development of the steam machines, that the manufacture left of being an artisan activity to be undertaken in industrial scale. From 1891, after the first electric station of London foundation, the London Electric Supply Corporation (LESCo), it possible to use machine tools powered by the new and modern electric alternating current motors. In order to have different output speeds from a gear box with one fixed input speed, several types of transmissions had been created, such as: pulleys and belts, gearboxes with sliding keys, Meander drive ("zig-zag"), jaw clutches (Ruppert mechanism), Tumbler gear (Norton type) or a mix of these types, having the change of the gears synchronized or not.
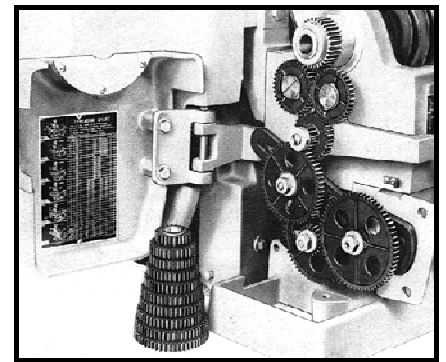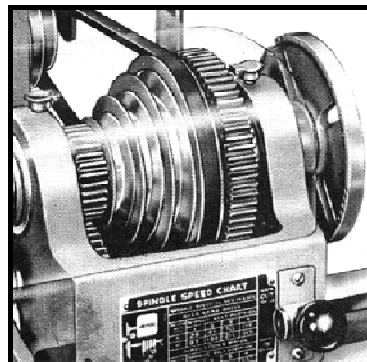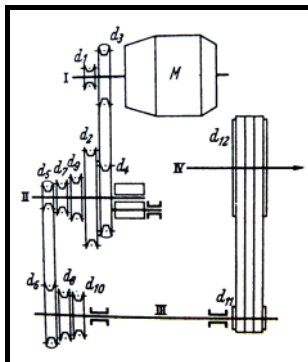

Figure 1 - (a) and (b) Belt step type speed variator and (c) changing gears.

The expert system present in this work is restricted to be used only to aid the design of basic speed variators of multiple and not conjugated axles. In these types of variators the relative motion between gears and axes can be fixed, when there is no degree of freedom, or sliding or rotational, when there is one degree of freedom.

The expert system proposed aids the mechanical engineering designer during the initial phase of design and specification, by using the computer to execute the repeated and boring tasks, when the errors are more likely to occur. It can also provide a substantial reduction of expended time in mechanical design, increasing efficiency and allowing evaluations of several different configurations of the gear box in a small period of time. It is important to notice that although expert systems should show the best result according to engineering design criteria to aid the designer the final decisions must be done by him.

The expert system presented in this work has the task of determination of the teeth number of machine tool gearboxes, considering two main criteria: the error in the final rotations and the smaller gearbox. Starting from these assumptions the program tries to find the best solution according to the input data and gives the speed diagram [1] for the chosen gearbox.

The program was developed (written) in Visual Basic Express 2005 compatible with Windows 98/SE/2000/XP, witch is very well spread, reliable, with a friendly interface, freeware and now supported by all classes of Microsoft Framework.NET translated in the future to several new systems.

2. PHASES OF THE DESIGN OF STEPPED SPEED VARIATORS

For the correct design of speed variator the following input data are needed: transmitted power, input speed and output maximum and minimum speed. Then, the phases of the design are:

1 – Calculation of the number of the output speeds (input data of the software).

The output velocity of a speed variator depends on the ratio between the maximum and minimum output cutting speed. The intermediate speed inside its range will be calculated following a scheduling rule that was presented by the Russian Academy of Sciences (Academician A. Gadolin) in 1876. In machine tools, for a good efficiency of the machine and the tools, the fall of the speed must be small and uniform throughout all the speed range. It was shown that the series of speeds that gives best performances are the geometric and arithmetic distribution. This work will contemplate only geometric series witch is formed in the following way:

$$n_2 = n_1 \times \varphi \; , \; n_3 = n_1 \times \varphi^2 \; .... \; n_m = n_1 \times \varphi^{m-1} \; \Rightarrow \tag{1}$$

$$\Rightarrow \quad \varphi = {}^{(m-1)}\sqrt{\frac{n_{max}}{n_{min}}} \tag{2}$$

2 – Calculation of the geometric serie ratio of the gear box.

Figure 2 shows several speed charts or diagrams. All of them are different configurations for the same gearbox. In order to find the best one, i.e. the most efficient, the smaller the number of teeth, the most compact and consequently the less expensive is the gearbox. Several methods, analytical and graphic, have been developed and are available in the technical literature, to aid the search for the best choice of gearbox configuration.
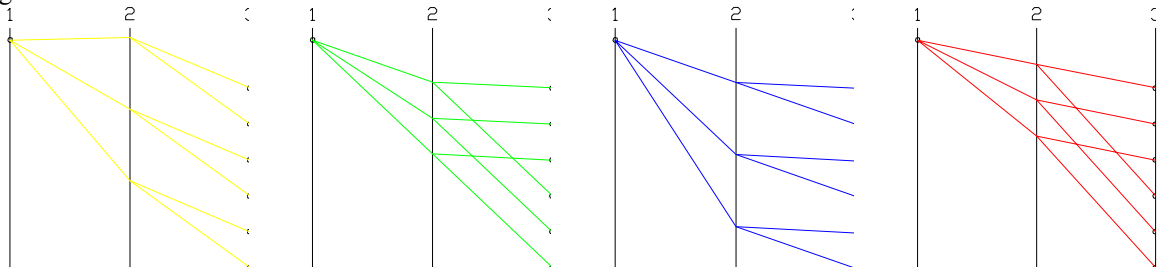

Figure 2 – Charts of the possible speed configurations for a 6 output speed variator.

3 – To build the sketch of a preliminary design for the speed variator (figure 3) and to plot the charts (figures 4, 5 and 6) for the possible configurations of the speed variator.
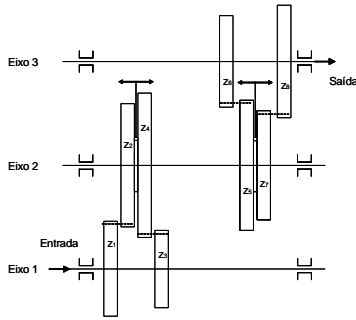
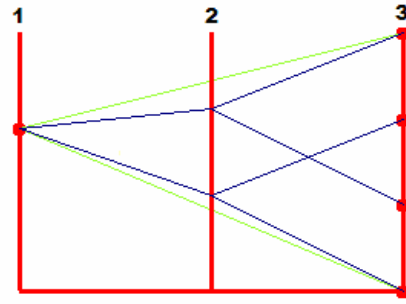Figure 3 - Possible schematic solution for the speed variator.

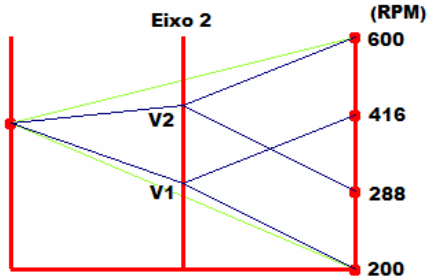Figure 4 – Possible speed diagram solution for the problem
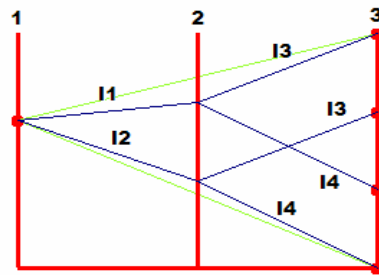

Figure 5 – Detail of the output speed

Figure 6 – Graphic representation of the gear ratio

4 – To evaluate the intermediate gear ratio through the inclination of the straight line segment in the speed diagram and using the parameters found by the equations below.

- gear ratio: $i = \dfrac{z_1}{z_2}$ (3)

- pitch diameter: $d_1 = z_1 \times m$ (4)

- center distance: $c = \dfrac{(d_1 + d_2)}{2} = \dfrac{(z_1 + z_2) \times m}{2}$ (5)

- total sum of number of gear tooth: $\Sigma z_{corresp} = (z_1 + z_2) = (z_3 + z_4) = c^{te}$ (6)

5 – Calculation of the number of teeth of each gear, according to design criteria.

6 - After the gear teeth number and the power transmission have been found, it is possible to carry with the gearbox design by doing the calculations for the selection of the principal mechanical elements like: shafts, bearings, keys and splines.

The gear ratios are given by the ratio of the tooth numbers of both connected gears. (eq.3). To obtain a ratio formed by rational numbers, some times is necessary to change the ideal engagement for a possible one. Then, an error in the final speeds must be admitted and/or be considered the increase of the tooth number. According to standar ISO 2299 (1973) the values of cutting speed and feed rate of machine tools, the acceptable output speed error in mechanical devices is from -2% to 3%. According to standard DIN 804 this value is reduced to the range -2% to 2%, which is the value adopt in this work, but could be modified by the user.

The proposal of this software is exactly to find the minimum number of teeth of a gear, for a given module, that the gear pitch diameter is correct (eq. 4) for the simulated variator. Although the software finds an ideal solution for the engagements of the gears, it allows the designer to modify the number of teeth before the calculation of the necessary gearing to reach the ideal theoretical engagement. Despite the fact that for machine tools there are standards for values of cutting speed (DIN 804) and feed rate (DIN 803), the software was developed in a way that permit the designer to find any solution to any kind of speed variator, only indicating the number of output speeds and the value of the maximum and minimum output speed.

Manual calculations for up to 3 axles speed variator are not very hard to find, however for more complex configurations like shown in figure 7, below, the task is much more laborious and difficult and makes the use of the software useful and attractive.
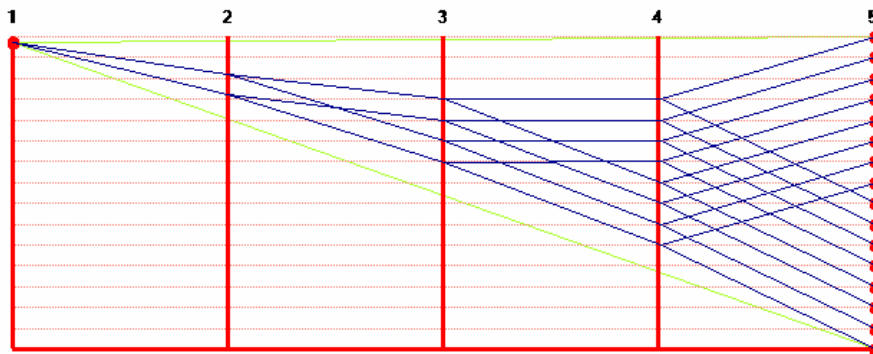
Figure 7 – Speed distribution in the exponential speed diagram chosen as a solution for the considered problem.

3. MAIN CHARACTERISTICS OF THE PROGRAM

The installation program will guide the user during the installation process. When the installation disk was accessed and the INSTALAÇÃO.EXE file executed it will check if the necessaries accessory programs needed to the correct execution are installed: Windows Installer and Framework.NET 2.0. If not, they will be automatically installed. Once the task is concluded the next dialog box will be shown (figure 8a e b)
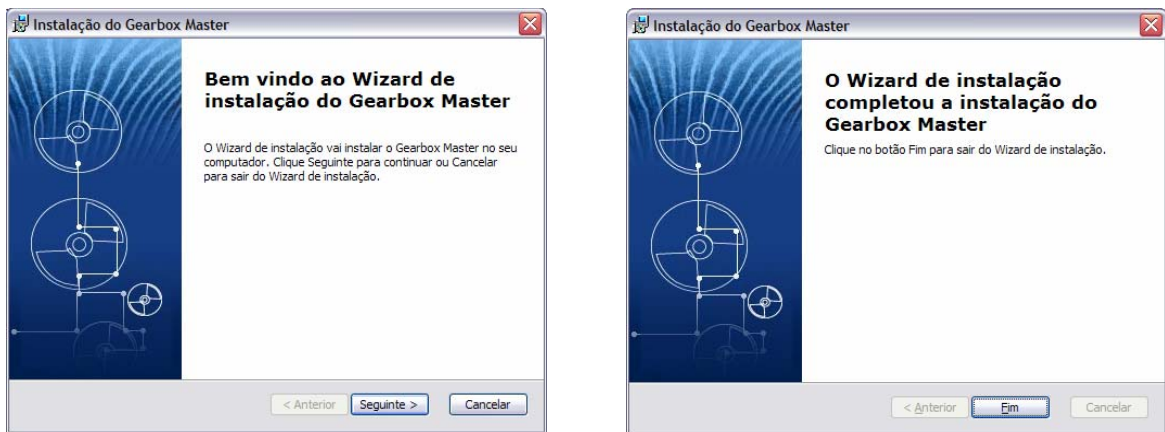

Figure 8 – Installation (a) and presentation (b) screen of the Gearbox Master program.

The first screen (figure 9a) is used to insert the initial data of the speed variator. The design limits are inserted in the same dialog box (figure 9b).
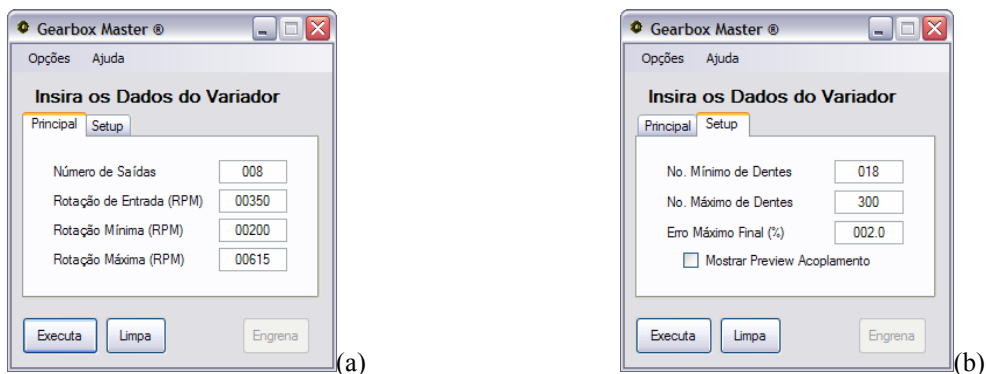

Figure 9 (a) Screen of initial input data and (b) the design limits.

Pre-defined values of the parameters for the gear boxes are presented when the Gearbox Master program is, initiated. The values of these parameters can be changed, saved or loaded from a file before the software starts the calculation loop for searching the ideal configuration of the gear box. The calculation starts by clicking the "executa" bottom. Then the following steps are undertaken:

1. Evaluation of the assembly possibility of the variator; if not indicates which errors is occurring.

2. Creation of a basic speed distribution chart (Figure 10).

3. Evaluation of the speed distribution inside the gearbox, checking if the smallest reductions/multiplications are being used. If not the button "Corrige" is shown and when it is clicked the software allows the correction of the problem.

4. Creation of a basic report in which is presented all the selected speeds of the theoretical diagram of the initial problem.
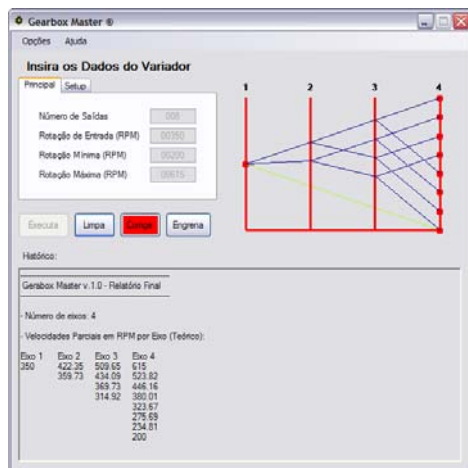

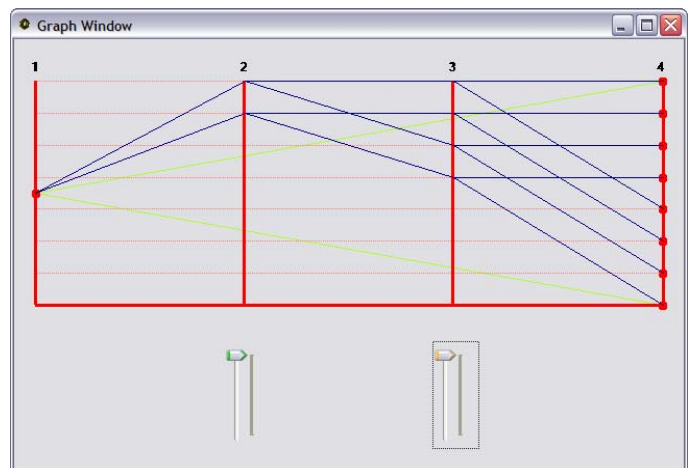Figure 10 – Execution screen of the Gearbox Master program

Figure 11 – Edition screen of the Exponential Diagram.

The diagram on figure 10 shows that the rate of reduction is greater than the multiplication of the value of the speed from shaft 3 by the speed from shaft 4. This is not the best configuration for an efficient performance of the gearbox. To cope with that, Gearbox Master allows the user to modify the speed diagram by two ways: manually and automatically. In the first case, by clicking on the graphic and a new screen opens (figure 11) where is allowed the edition and the new graphic and corresponding velocities are presented. The new values can be saved by clicking the graphic again.
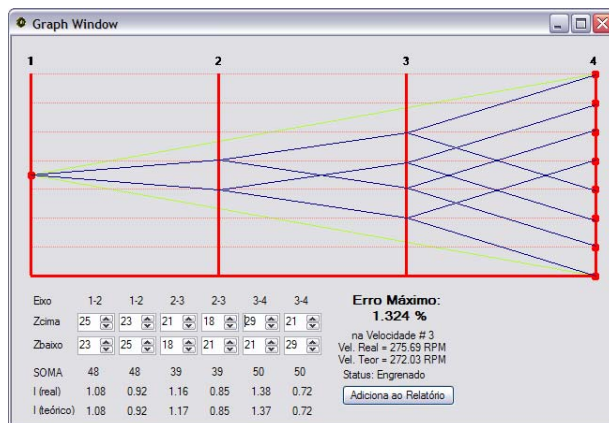

Figura 12 – Manual edition screen showing another solution for the problem.
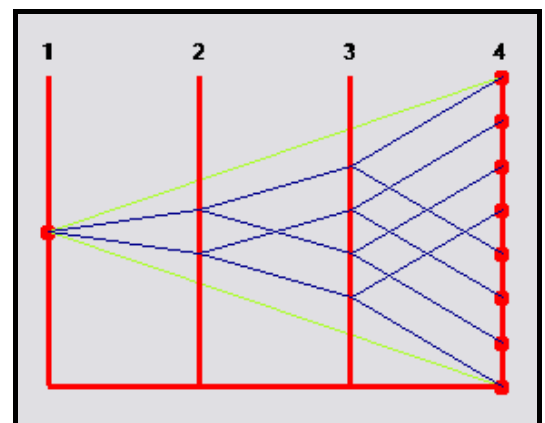
Figure 13 – Detail of the exponential diagram automatically calculated after the execution of the corrige button.

In the second case (figure 12) the button Corrige will appear. This option allows the automatic correction of the speed diagram to find a new configuration for the gearbox with the smaller ratio of reduction/multiplication according to the needs of the project (figure 13).

The main routines of the software are performed when clicking the "Executa" button. Besides the evaluation of all the input variables of the program this procedure executes many others sub-procedures that will determine

initial and theoretical speed distribution, draw the exponential diagram of this distribution and generate the first report with the output speeds and number of the teeth of the gears.

In the procedure cria_germar the main matrix of the program called the Germar matrix that contains all speeds. The number of lines of this matrix is the same of the number of output speeds and the number of columns is the same of the number of axles of the speed variator. In this procedure this procedure is fed with the input speed and the other values are calculated by clicking "Executa" button. After that, the results are shown in the first report.

To find the elements of this matrix it is necessary to determine the value of φ and also the output speeds. These values are calculated in the procedures "cria_fi" and "cria_saidas", respectively. The intermediate speeds are obtained based on the type of engagement chosen.

The procedure completa_germar exactly comes to fill the matrix with these speeds, following some especific rules. With the intent to find the shortest dimensions of the variator, a graphical/iterative method for the development of the speeds was developed. In the Exponential Diagram, each one of the straight blue lines represents an engagement and their inclination represents the intensity of the gear ratio (multiplication or reduction). That is, the steeper the inclination of the line in the diagram, the greater the gear ratio and therefore large gears will be necessary to achieve the necessary coupling.

In order to minimize the gear ratio an algorithm was developed with some knowledge presented in literature.
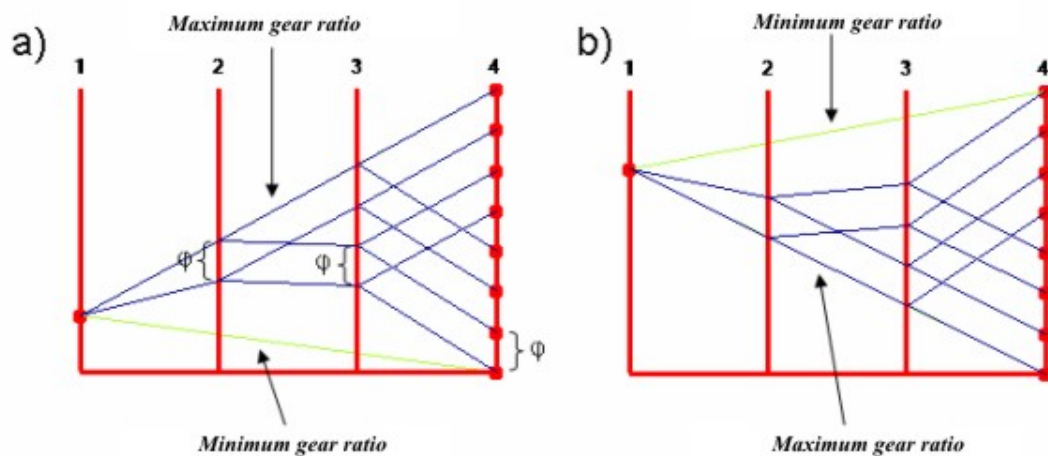

Figure 14 - Comparison of speed distribution of two speed variator with the same output. (a) For a low input rotation and (b) for a high input rotation.

This algorithm starts by finding straight lines, represented in figure 14 by the green lines, linking the input speed to the highest and lowest output speed. Then, it was assumed that the highest variator ratio corresponds to the straight line with the highest inclination. After that, an entire line of transmission would be found by the overlapping of this line, as shown in figure 14. The construction of the speed chart continues in a way that the number of gears for the output axle is chosen to reduce problems with vibrations. This is undertaken by drawing parallel lines defining all the other speeds of the problem.

This solution was very efficient for small variators (up to 3 axles), with few output speeds. However, with the increase of the number of output speeds and inside axles, it was evidenced that this solution did not present the smallest gear ratio, as shows the figure 15. It can be seen that although the engagements up to 4th axle were well solved, when adding the 5th axle the reduction ratio was greater than its upper limit.

An algorithm was created to cope with that when a "Correction" button is clicked. Then the algorithm finds the gears that make the same value for the multiplication and reduction rates of the gear box. This transmission rate makes possible to design the smallest gear box.

The designer may prefer not to use this algorithm if the size of the gear box is not important. An advantage of this system is that the parameters of the gear box can be chosen by the designer.

The correction procedures can be undertaken by the do_correct function and if necessary by the "Correction" button.

After the velocities are chosen, it is necessary to find the search for the gears that gives the smallest error in the rate of the transmission by clicking the "Engrena" button. Then the *Germar* matrix is processed to choose the gears doing several interactions based on the given conditions, until to find a satisfactory solution. The designer can chose to have the results plotted from each interaction.
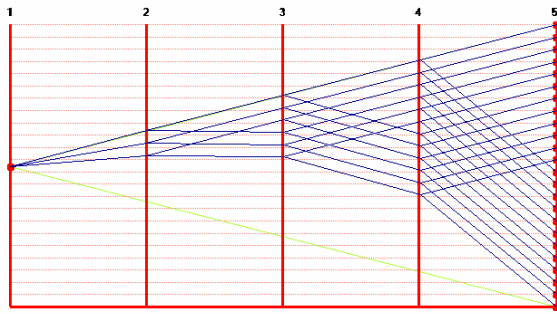
Figure 15 – Example of inconsistency in the applied method in a 24 speeds variator.
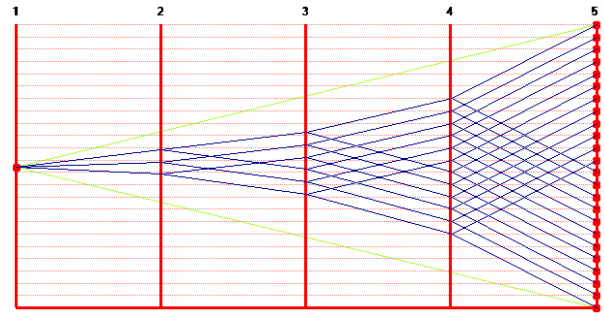

Figure 16 – Example of solution presented for the correction algorithm.

This algorithm can also to indicate that there is not possible solution for a particular condition, for example, the height of the gear teeth.

Several routes can be used to test different gear teeth for a particular transmission by using the manual mode, and this way, finding a rate transmission smaller that its upper limit.

The steps followed by the algorithm to find the best solution for a particular transmission are:

1. The first and the most important step is the execution of the "determina_eixo" routine, which is used to find the axes position for each transmission from a given matrix of gears. This matrix contains the number of teeth of each gear and in which axe is this gear connected.
2. In the second step, the "engrena_corrigido" routine is executed to find the actual transmissions to be used in the gear box. This routine creates a matrix "germarAUX" to calculate the parameters for the transmissions chosen by the user. After that, a new matrix called "Sum_MAX" in which each element is the sum of the number of teeth of each pares of gears connected. Then the routine starts a loop to search for the gears to be connected to obtain an output velocity inside of the specified range until it is found.

The main actions taken inside this loop are:

−   To reduce the error in each gear coupling.
−   Verify if the chosen gears according with the search criteria and if the output velocities are corrected.
−   In case of output velocities errors, to execute the "Engrena" routine for each pair of gears connected;
−   Check erros;
−   Run the "Engrena_Coluna" routine to find pairs of gears with the same number of teeth;
−   Check erros;
−   The o Diagram of the gear box can be plotted at the end of each interaction of the loop, that can be seen by the user as an animation of the process.

After these steps, a report is written by the software with relevant information about all couplings of gears inside the gear box.

4. CONCLUSIONS AND FINAL COMENTS

The development of software for speed variators design is very important, because several machine and equipments still uses this kind of transmission. Unfortunately there are not recently works available with new information about speed variators. A quick search in the literature and associations like AGMA, DIN, ISO e ABNT show the absence of new information about this type of equipment.

Based on works that date from earlier 1970's an algorithm of resolution of the problem was developed and with that a computer program with the necessary interface to aid the variator design. The Gearbox Master program not only presents a computational new method for solution of problems in a variator design, but also eliminates the hard work of the designer in doing the repeated manual calculations using the same formulas and table interpolations several times. Even with its restrictions, the program still presents certain flexibility to solve the problem and find an adequate solution.

After several tests, it can be said that the Gearbox Master performance is as expected due to its capacity to find an optimized solution to the most diverse models of variators. This program will aid students and engineers in variators design, avoiding manually calculations as made before.

The developed algorithm offers to the mechanical engineer a powerful tool find, with rapidity, efficiency and exactness of calculations, the most important characteristics of axles and gear transmission. It is important to observe that the user has the total control of the project. All decision must be made by him; the program only

gives the orientation and shows the calculation results. The algorithm was elaborated and developed with special concern in been as simple, efficient, auto clarifying and of easy understanding as possible, and let the task of design undertake in a friendly and pleasant environment.

Suport Operational Systems: Windows 2000 Service Pack 3; Windows 98; Windows 98 Second Edition; Windows ME; Windows Server 2003; Windows XP Service Pack 2

Needed Softwares: Windows Installer 3.0 (except for Windows 98/ME, witch requires Windows Installer 2.0 or latter). Windows Installer 3.1 or latter is recomended. IE 5.01 or latter: the Microsoft Internet Explorer 5.01 or latter must be executed for all .NET Framework installations.

Required disk space: 280 MB (x86), 610 MB (x64)

It is important to remember that the use of the operational system with valid license is extremely important so that the Windows Update can effect the necessary updates of security in the system, as soon as will be available.

This program is a expert system of the module MACHINES ELEMENTS, part of the Computational System of Project, developed in *Computer Aided Design Lab.* – LEPAC of DEM/UFRJ. Other expert systems already developed or in development phase, such as: threaded fasteners and power transmission screws, keys and sliding keys, V-belts, spur gears, roller chains and helical springs. The chaining of these expert systems will allow efficient and fast development of machine design.

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