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ON THE USE OF THE VAUCANSON PLANETARY TRANSMISSION IN THE RENEWABLE ENERGY SYSTEMS. PART II: POWER CIRCULATION AND EFFICIENCY

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ABSTRACT
The paper main objective is to model and analyze the properties of the Vaucanson planetary transmission for using it as reducer or amplifier in the renewable energy systems. The power circulation and the efficiency of the initial Vaucanson reducer are presented in the second part of the paper. On the basis of the presented properties, useful conclusions for the use of the transmission in renewable energy systems are formulated.
Keywords: Vaucanson planetary transmission, power circulation, efficiency

1. INTRODUCTION
The structural characterization, the kinematical and static features of the planetary reducer of Vaucanson type are presented in the first part of the paper. The results are further used in the transmission dynamic modeling. Thus, the reducer power circulation and efficiency are modeled, analyzed and optimized in this second part of the paper with the aim of using the considered transmission in renewable energy systems, either as speed amplifier or speed reducer.

2. MODELING OF THE POWER CIRCULATION AND EFFICIENCY
On the basis of the results, obtained in part I, for the *reduced angular speeds* and for the *reduced torques*, there can be established the power *theoretical circulation* (without friction) and the *power real circulation* (with friction).
The following values for the branches of the power *theoretical circulation* are obtained from relations (3) and (6) from part I:

$$\begin{aligned}
\omega_5 T_5 &= (+1)(-22) = -22 < 0 \text{ (output power for unit 2);}\\
\omega_4 T_4 &= (+20/23)(+25{,}3) = +22 > 0 \text{ (input power for unit 2);}\\
\omega_6 T_6 &= (+1)(+23) = +23 > 0 \text{ (input power for unit 3);}\\
\omega_7 T_7 &= (-20/22)(+25{,}3) = -23 < 0 \text{ (output power for unit 3);}\\
\omega_1 T_1 &= (-20/22)(-25{,}3) = +23 > 0 \text{ (input power for unit 1);}\\
\omega_3 T_3 &= (+20/23)(-25{,}3) = -22 < 0 \text{ (output power for unit 1);}\\
\omega_H T_H &= (-1/50{,}6)(+50{,}6) = -1 < 0 \text{ (output power for unit 1);}
\end{aligned} \qquad (1)$$

on the basis of these values, it was illustrated the power theoretical circulation from Fig.1,a, which highlights the existence of a power circulation in closed circuit, 22 times bigger than the input power. Analogous, from relations (3) and (8) from part I there are obtained the following values for the branches of the power *real circulation*:

$$\omega_5 T_5 = (+1)(-2{,}9494) = -2{,}9494 < 0 \text{ (output power for unit 2);}$$
$$\omega_4 T_4 = (+20/23)(+3{,}6083) = +3{,}1376 > 0 \text{ (input power for unit 2);}$$
$$\omega_6 T_6 = (+1)(+3{,}9494) = +3{,}9494 > 0 \text{ (input power for unit 3);}$$
$$\omega_7 T_7 = (-20/22)(+4{,}0837) = -3{,}7124 < 0 \text{ (output power for unit 3);}$$
$$\omega_1 T_1 = (-20/22)(-4{,}0837) = +3{,}7124 > 0 \text{ (input power for unit 1);}$$
$$\omega_3 T_3 = (+20/23)(-3{,}6083) = -3{,}1376 < 0 \text{ (output power for unit 1);}$$
$$\omega_H T_H = (-1/50{,}6)(+7{,}6920) = -0{,}1520 < 0 \text{ (output power for unit 1);} \tag{2}$$

on the basis of these values the reducer efficiency was established:

$$\eta_{a,H} = (-\omega_H T_H)/(\omega_a T_a) = (-\omega_H T_H)/1 = +0{,}152 = 15{,}20\% \tag{3}$$

and it was illustrated the power *real circulation* from Fig. 1, b, which highlights the existence of a power circulation in *closed circuit*, 2,9494 times bigger than the input power. It is also detected that the module of the output power (see Fig.1,b) is much smaller than the module of the sum of the powers lost through friction, in the three component units.

3. CONCLUSIONS

1°. In the conditions of the considered example, the *Vaucanson's* reducer (see Fig.3, a) is characterized through the following properties:

a) it is a 1 DOF planetary mechanism with one input and one output, which has a relative reduced degree of complexity;

b) it transmits the speed from input to output in the conditions of reducing it 50,6 times;

c) it transmits the power from input to output with a reduced efficiency (15,20 %), caused by the power circulation in closed circuit, which exceeds 2,9494 times the input power (see Fig.1,b); due to the reduced efficiency, the torque is transmitted from input to output with a diminished amplification: of only 7,692 times, instead of 50,6 times!

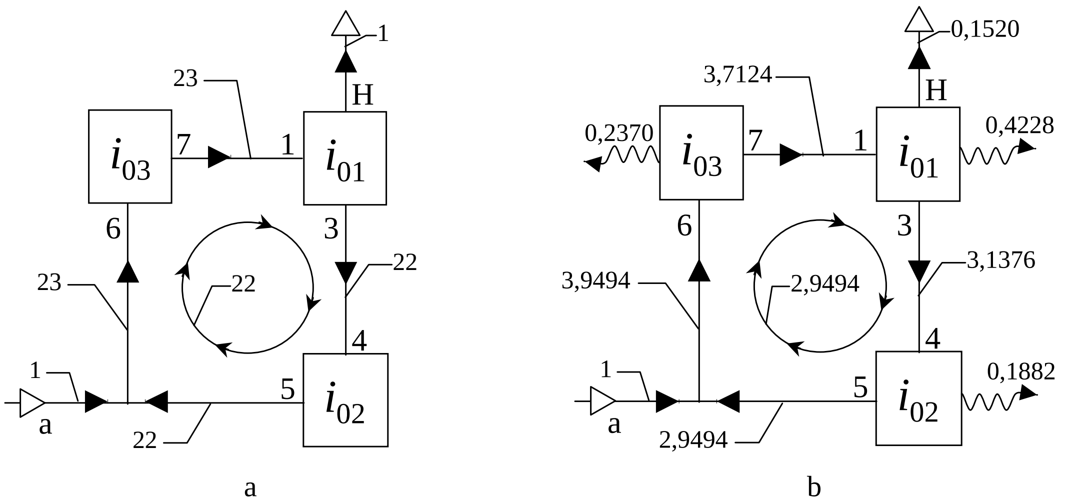
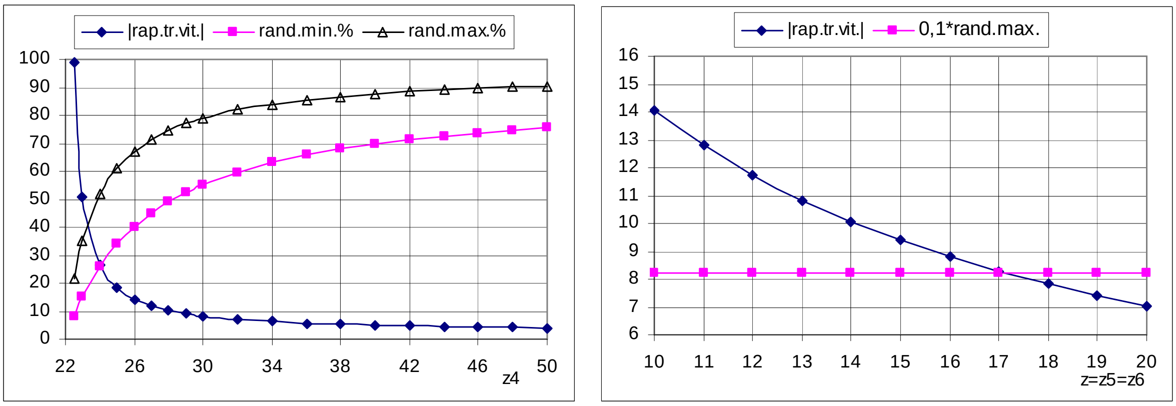


Figure 1. The circulation of the power branches in the Vaucanson planetary reducer: a) the scheme of the power circulation, while neglecting friction; b) the scheme of the power circulation, while considering friction.



a b

Figure 2. The diagrams for the variation of the transmission ratio module $|i_{a,H}|$ *and of the efficiency* $\eta_{a,H}$*,: a) in terms of the teeth number* z_4 *(the diagram rand.min. was obtained in the premise that* $\eta_{01} = 0{,}94^2 \cong 0{,}883$ *and* $\eta_{02} = \eta_{03} = 0{,}94$*, and the diagram rand.max. was obtained in the premise that* $\eta_{01} = 0.98^2 \cong 0{,}96$ *and* $\eta_{02} = \eta_{03} = 0{,}98$*); b) in terms of the teeth number* $z = z_5 = z_6$*.*

2°. For a better highlighting of the correlation between the speeds transmission ratio (considered in module: $|i_{a,H}|$) and the efficiency ($\eta_{a,H}$), in Fig.2,a there were plotted the diagrams of variation for these parameters (|rap.tr.vit.| and rand.min.), in terms of the teeth number z_4 (see Fig.1,b from part I); according to Fig.2,a, the increase of the ratio $|i_{a,H}|$ is accompanied by the efficiency reduction and reciprocally: while the ratio $|i_{a,H}|$ is reducing, the efficiency is increasing.

3°. The following modalities can be used, separately or combined, for the efficiency optimization:

a) Use of gear pairs with maximum efficiencies (processed very careful); in order to highlight this aspect, in Fig.2,a it was superposed the diagram of the efficiency *rand.max.=maximum efficiency*, obtained in the premise that the component units (see Fig.1,c and d from part I) have maximum interior efficiencies: $\eta_{01} = \eta_{H1,3} \cong \eta_{H3,1} = 0{,}98^2 \cong 0{,}960$, $\eta_{02} = \eta_{4,5} \cong \eta_{5,4} = 0{,}98$ and $\eta_{03} = \eta_{7,6} \cong \eta_{6,7} = 0{,}98$. The comparative analysis of the diagrams *rand.min.=minimum efficiency* and *rand.max.=maximum efficiency*, (Fig.2,a) shows that, in the second case, the efficiencies are much better.

b) *Replacement of the closing kinematical chain* 4-5 ≡ 6-7 (see Fig.3, a), through a system consisting of two electrical machines, one of which works as motor and one as generator.

c) *Identification of the optimum number of teeth* $z = z_5 = z_6$ (see Fig.3, a); according to Fig.2, b, by modifying the teeth number z, the efficiency remains unmodified, while the transmission ratio has a significant variation.

4°. By inverting the power circulation direction (see Fig.3,a), the Vaucanson transmission could become a speed amplifier; in the considered numerical conditions, this is not possible because the efficiency becomes negative ($\eta_{H,a} < 0$):

$$\eta_{H,a} = (-\omega_a T_a)/(\omega_H T_H) = \{(1 - i_{01})[i_{03}\eta_{03}^{x3} - i_{01}i_{02}\eta_{01}^{x1}\eta_{02}^{x2}]\}/[1 - i_{01}\eta_{01}^{x1}(i_{03} - i_{01}i_{02})] \tag{4}$$

due to the fact that the denominator from relation (4) is *always* negative, it outcomes that the Vaucanson transmission can function as a speed amplifier if the numerator is negative, too:

$$i_{03}\eta_{03}^{x3} - i_{01}i_{02}\eta_{01}^{x1}\eta_{02}^{x2} < 0 \Leftrightarrow i_{03}\eta_{03}^{x3} < i_{01}i_{02}\eta_{01}^{x1}\eta_{02}^{x2} \tag{5}$$

in which, for the speed amplifier: x1= -1; x2= -1 and x3= +1. Considering (see Fig.1 and Fig.3, a): $i_{01} = i_{1,3}^H = \omega_{1,H}/\omega_{3,H} = -z_3/z_1 = -1$; $i_{02} = i_{4,5} = +z_5/z_4 = +z/z_4$; $i_{03} = i_{7,6} = -z_6/z_7 = -z/z_7$; $z_7 = 22$; $\eta_{01} = \eta_{1,3}^H \cong \eta_{3,1}^H = 0{,}94^2 \cong 0{,}883$, $\eta_{02} = \eta_{4,5} \cong \eta_{5,4} = 0{,}94$ and $\eta_{03} = \eta_{7,6} \cong \eta_{6,7} = 0{,}94$, relation (5) becomes (whatsoever the value of z):

$$z_4 > z_7/(0{,}94)4 = 22/(0{,}94)4 = 28{,}1798 \Rightarrow z_4 = 30. \tag{6}$$

5º. Tacking into account conclusion 3ºc (see Fig.2, b), the transmission modification according to Fig.3, b is proposed, in which it is considered that $z=z_5=z_6=11$. Considering the previous values of the interior efficiencies and the teeth numbers (η_{01} = 0,942, $\eta_{02} = \eta_{03}$ = 0,94, $z = z_5 = z_6 = 11$, z_4= 30, z_7 = 22) the variant of the Vaucanson transmission from Fig. 3,b can function both as a speed reducer, with the speeds ratio $i = \omega_a/\omega_H = -15$ and the efficiency $\eta_{a,H}$ = 0,5688 = 56,88%, and as a speed amplifier, with the same speeds ratio but with a more reduced efficiency: $\eta_{H,a}$ = 0,207 = 20,7%; if using a technology with high accuracy, which ensures interior efficiencies like η_{01} = 0,982, $\eta_{02} = \eta_{03}$ = 0,98, the reducer efficiency becomes $\eta_{a,H}$ = 79,95% the amplifier efficiency becomes $\eta_{H,a}$ = 77,6%. Thus, by increasing the technological accuracy, the difference between the efficiencies as speed reducer ($\eta_{a,H}$) and as speed amplifier ($\eta_{H,a}$) is significantly reduced.

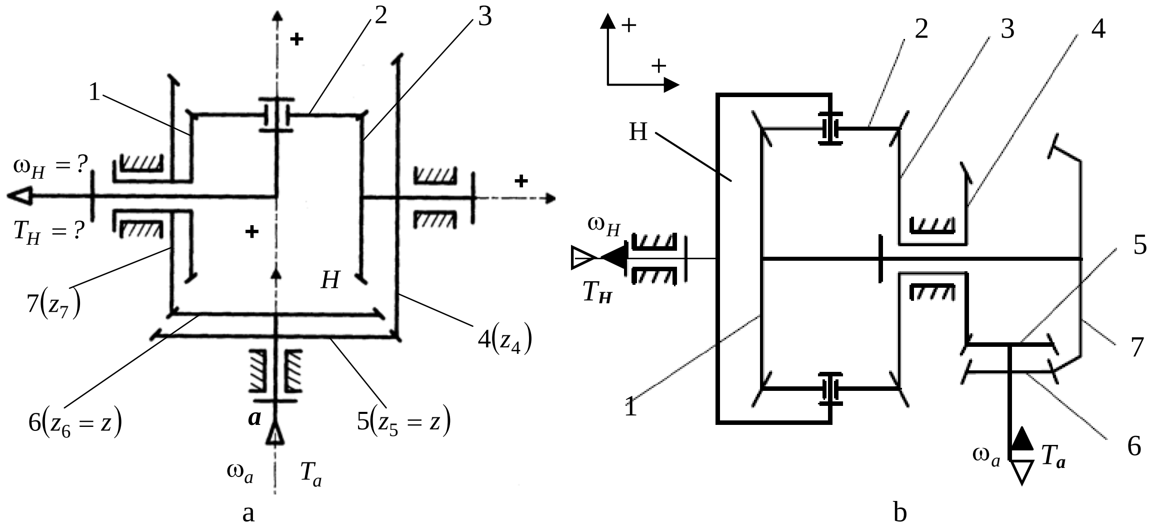


Figure 3. a) Scheme of the initial Vaucanson's planetary reducer; b) Vaucanson variant, optimized on the basis of the paper conclusions, which can be used either as speed amplifier or as speed reducer.

6º. In the variant proposed in Fig.3,b, manufactured in proper technological conditions, the planetary transmission of Vaucanson type can be used either as speed amplifier, in the equipments dedicated to the wind turbines and small hydro stations [3], and as speed reducer, in the equipments for the solar panels tracking systems [5] and for waste processing, as well as in other applications.

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