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CONCEPT AND MODEL OF TERRAIN WHEELED TRACTOR WITH HYBRID DRIVE

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Abstract

The article presents construction concept of a tractor with hybrid, diesel-hydraulic and diesel-electric drive meant for the use in livestock holdings. The tractor is enabled to cover short distances with the combustion engine switched off. This solution uses independent engines to propel front and rear axles. This article presents a computer model and simulation results for the project of a hybrid, diesel-electric tractor based on a benchmark machine Fendt 516.

Aside from the ability to drive with diesel engine switched off, the proposed solution has additional positive features allowing smooth transition of relation of peripheral speed of the front and rear wheels. It enables to obtain higher tractive powers for various conditions in a broader range than for a traditional solution (with propelling both axles with one engine through different transmission systems and specific difference of peripheral speed of the wheels). The computer model was built on the basis of the benchmark machine.

Keywords: *terrain wheeled tractor, hybrid drive, computer model of a tractor*

1. Introduction

The problem of controlling work of agricultural tractors, especially distribution of the power flow to the front and rear axles is one of the most important issues at designing and operating this basic agricultural machine. This issue is addressed by the leading tractor producers. They are searching for the most optimal transmission between the front and rear axles (the so-called kinematic discrepancy) and distribution of masses – individual axle's weights. Diversity of the works performed and grounds the tractors drive on impede clear determination of conditions in which the front drive should be switched on and off. The works over automation of switching the front drive were conducted at the Warsaw University of Technology (WUT) since the 1990s. The research concerning this issue was conducted in the period of 1990-2012 [12-15] in cooperation with the Agricultural and Technical Academy, transformed into the University of Warmia and Mazury. Despite obtaining satisfactory results, they were not implemented due to the crisis of the Polish tractor producers, which occurred during that period.

After quite promising results, it became clear that algorithms of the drive switching were adjusted only for typical grounds and agricultural works. The ideal solution would be the dynamic transmissions between the front and rear axles. It may be obtained by utilising two separate drives controlled by one computer. The solution considered involved hybrid drives: diesel-hydraulic and diesel-electric. Both solutions have their own advantages and drawbacks. In both cases, flexibility of work is obtained at the expense of efficiency resulting from extension of the chain of processed energy. However, the possibility of accumulating and reclaiming energy when braking and elimination of the phenomenon of circulating power, destroying the drive, may compensate for losses also from the energy point of view.

2. Development tendencies in agricultural machines

Similar to industry, agriculture also aims at the highest possible production efficiency. Development of technology in the scope of crops contributed to development of the so-called precision agriculture. This is the term defining the technologies forming the agricultural system, which allows adjusting all agrotechnical measures to the dynamic conditions on specific croplands [1]. The diagram of functioning of the precision agriculture was presented in Fig. 1.

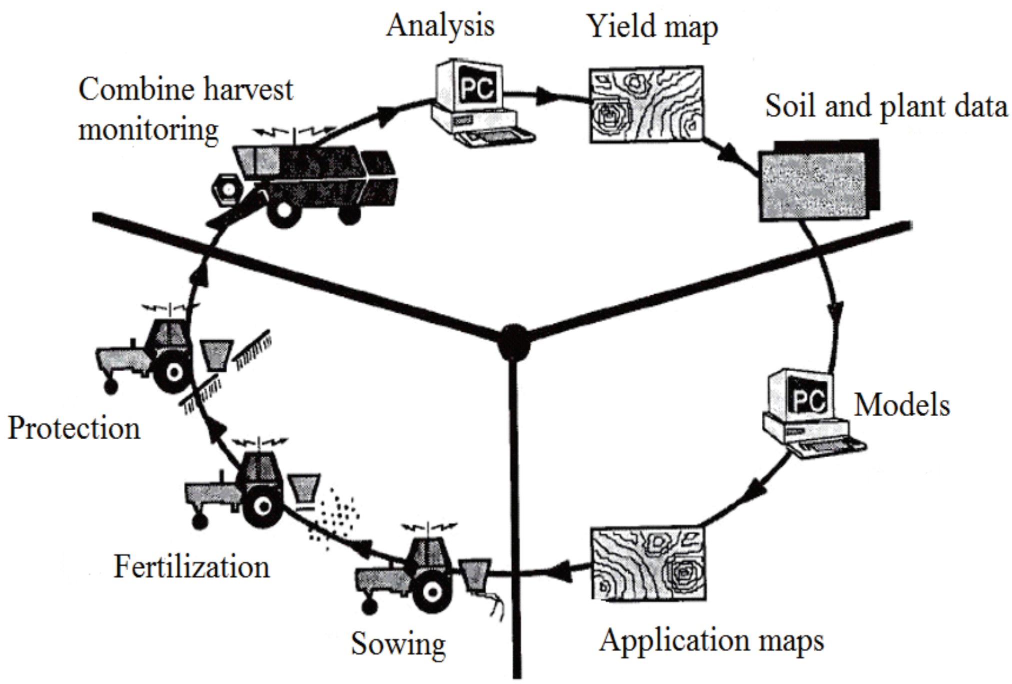

Fig 1. Precision agriculture organisation diagram [1]

Relevant technical resources are necessary for proper functioning of this system. Significant role is played here by automation of processes such as variable dosing of fertilisers and plant protection agents, based on the previously prepared maps, which would be virtually impossible using the conventional tools. The presently applied solutions utilising hydraulic systems controlled with solenoid valves enable meeting the requirements. However, utilising the electrical drive in the equipment enables easier implementation of automation systems and facilitates control over actuators.

3. Hybrid drive concept

Figure 2 presents diagram of a conventional drive of an agricultural tractor. Torque from the compression ignition engine is transmitted by the clutch to the gearbox. There, the drive is divided into the rear and front driving axle (added with clutch), power take-off shaft (WOM) and hydraulic pump drive of the lifting equipment.

Utilising hybrid drives in agricultural tractors is not a new idea. An example of a historic construction is the 1945 tractor IH Farmall 450 [6]. An example of another hybrid tractor is the 1959 Allis-Chalmers, which was the first equipped in a fuel cell [6].

The first modern tractor, which utilised electricity to drive, was the hybrid Eltrac E135. It was built in 1998 on the basis of the model of New Holland M135. This vehicle had six-cylinder charged ZS engine. It powered the generator, which was the energy supply for an electric engine interfaced to drive system and power take-off shaft (WOM). The tractor had 2 ranges of driving speed. 0-17 and 0-40 km/h, and with the WOM it was possible to take the power of up to 89 kW at standard speeds of 540/540E/1000 r.p.m. [6].

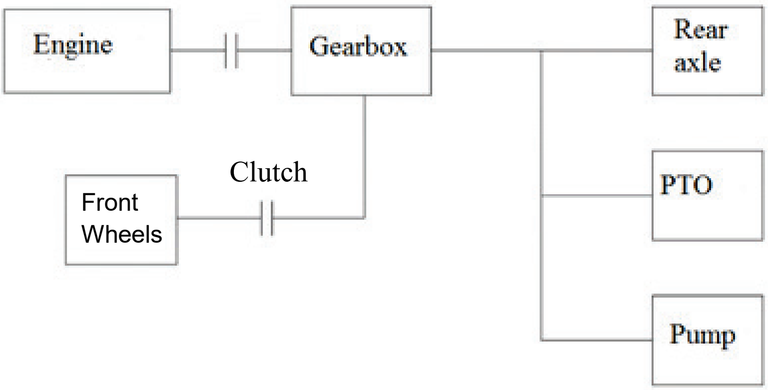

Fig. 2 Diagram of a conventional drive of an agricultural tractor

In the recent years, the agricultural machines electrification trend was noticeable. There are tractors installed with electric generators built into the engine case, or as an additional modules powered by the PTO (Fig. 3). There electric drive is used to power the equipment attached to the tractor.

Fig. 3. John Deer tractor with an electricity-generating unit powered by the front WOM as a balance weight

The above-mentioned examples present "classical" approach to the subject of the hybrid wheeled machines. This article presents another approach to construction of a tractor's drive. Diagrams of those drives are presented in Fig. 4. A typical mechanical rear axle drive and added independent front axle drive powered from a different source were utilised there. It is electric in the first concept and hydrostatic in the second one. Both drives are equipped in storage cells for storing and reclaiming the energy. In the case of the electric drive, the classical PTO was discarded. It was replaced with a socket, which may be used for powering the attached equipment. Such solution enforces retrofitting the equipment with additional electric engines, but facilitates their precise control, in accordance with the rules of precision agriculture. Control of the AC motors is performed with utilisation of an inverter placed next to each of them.

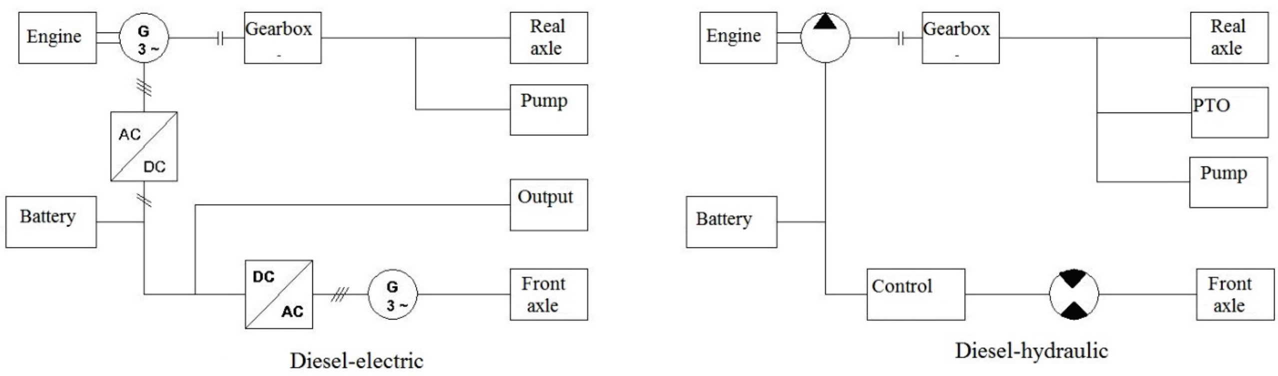

Fig. 4. Diagrams of hybrid drives of an agricultural tractor

4. The benchmark machine parameters

The benchmark tractor, Fendt 516, was used for further analyses of the concept of the hybrid drive: diesel-electric. It is a heavy tractor with an all-wheel-drive with an unladen weight of 6400 kg and a nominal power of 110 kW (150 KM). The wheelbase in the vehicle is 2560 mm. Tyres assumed for further simulations: front: 540/65R28, rear: 650/65R38, by Trelleborg [9].

5. Construction of the hybrid tractor computer model

Construction of the mathematical model involves knowledge of specific operation principals of the drive of a tractor and mathematical equations describing them. In general, modelling is connected with abstracting certain real features of an object, which are interesting to us and ignoring the less important ones, not having a significant influence on the phenomenon we wish to observe. In practice, it means using simplified equations, which usually involve indicators determined with experiments and characteristics prepared on the basis of measurements. Often, to replace the complicated elements with much simpler ones, there is also applied the probability of the principle of operation and the phenomena occurring in the modelled objects.

The drive will be presented as a "flow" model, in which the relations between specific blocks corresponding to the sub-components of the tractor are described with the flow of signals standing for values such as: rotational speed, torque, voltage and current. The diagram presenting the idea of functioning of such a model was presented in Fig. 5.

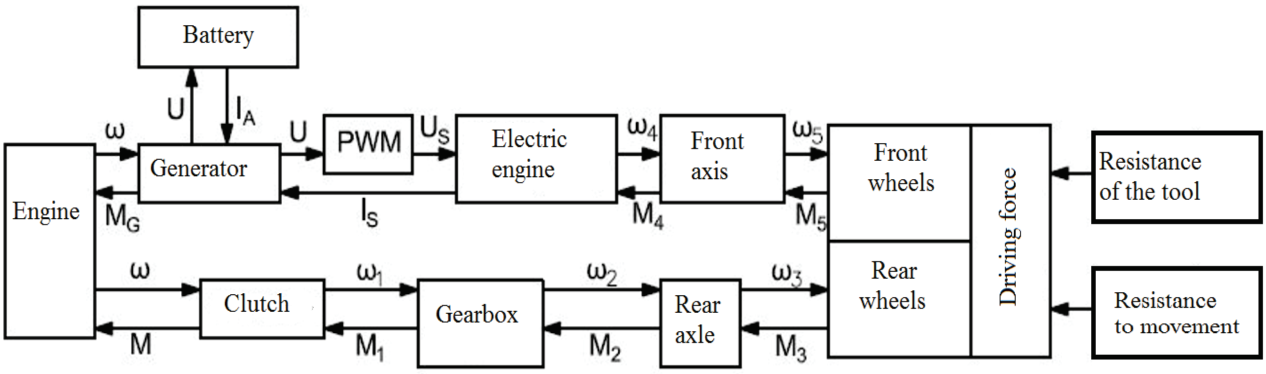

Fig. 5. Diagram of a "flow" model of the drive of the hybrid tractor [3]

The computer model of the tractor was created in the MATLAB/Simulink program, as part of one of the subject-related Master's Degree theses at the Warsaw University of Technology [3]. It is a flat model, also known as "bicycle" model. Wheels on one axle are treated as a whole, disregarding the difference of adhesion coefficients of those wheels and the phenomena occurring within the differential gear. Methodology of creating the model of a typical tractor was based on [5] and [8]. Only the added elements of a hybrid tractor will be discussed further in the text.

Model of the Diesel engine will be based on the reading of the values from the external characteristics. Electric engine for the front axle drive will be an AC machine. Due to similarity of the phenomena occurring in the engine itself, an attempt was made to model it as a DC engine. Lithium-ion cells were used for storage of the electric energy in the vehicle. Due to good parameters, these cells are increasingly used in electric vehicles. They characterise with high energy density, sometimes exceeding 160 Wh/kg [4]. Moreover, they have long service life, which is also their significant advantage.

Model of the storage cell is based on reading from the characteristics. Both the output voltage and the charging current depend on the cell charge level. Those dependents were prepared for the volume specified in a percentage value, which enables quick change of sizes of the modelled element. Initially, the adopted volume of the cells was equal to 30 Ah, providing approximately 20 kWh of energy for the voltage in the system.

Another element of the model is wheels, which are to change the torque into the forces applied to the surface. Adoption of the flat model allows replacing the whole axle with one block. The fact that examining the traction properties of the tractor involves work in the field requires application of the equations describing movement of a wheel on deformable surface. Due to the fact that deformability of the surface affects resistance to motion in the greater extent than deformability of the tyre itself, it is possible to assume in the first approximation the model of a rigid wheel [2] with constant dynamic radius. The propelling force created below the wheel may be described with an equation [7]:

$$F = N \cdot \mu(\sigma), \tag{1}$$

where:

F – Propulsive effort created below the wheel,

N – pressure on the wheel,

μ – traction coefficient dependent on skidding σ, according to the characteristics in Fig. 6.

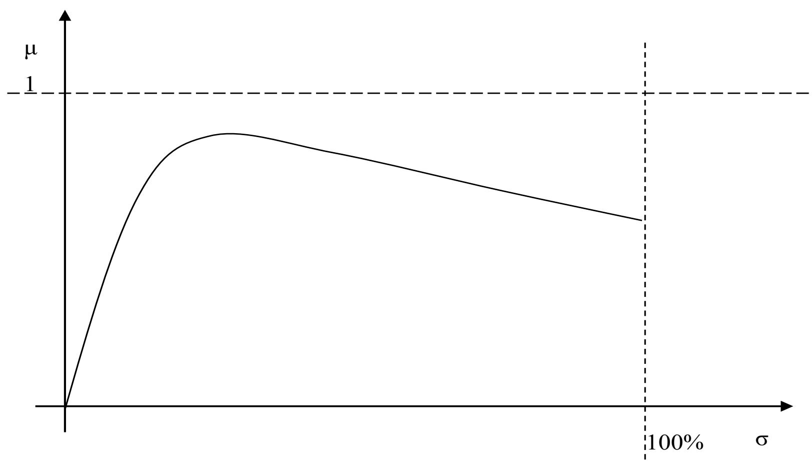

Fig. 6. Typical dependence of the μ traction coefficient on σ skidding

The torque obtained on the wheel may be determined as a product of propulsive effort and dynamic radius of the rear wheels. The propelling force (F) [2] generated by the wheels is lower than the propulsive effort *Fn* by tyre rolling resistance *Ft.* Their value depends on the pressure of the wheel onto the surface and the tyre rolling resistance coefficient *f.* Speed of the rear wheels is used to control the speed of the wheels of the front axle. Moreover, structure of the model enables reading of the value of the wheels skidding.

For the correct description of operation of the tractor, it is necessary to determine the forces applied to it during work and entering them into the model. They were determined according to the methods described in [2, 11].

6. Hybrid drive analysis

The build model of a hybrid drive was subjected to tests. The purpose of the tests was comparing the effectiveness of the tractor with conventional – mechanical coupling of the front and rear axle drives with the kinematic discrepancy determined by the producer – with the front axle propelled with an electric engine. In the case of the conventional solution, the driver has a slight impact on the kinematic discrepancy. He may modify it only through the level of pressure in the tyres and distribution of the wheel load regulated with dead weights. However, this action constitutes only adjusting the parameters of the tractor to the specific surface and ground formation. [10] In the case of the hybrid drive, the regulator controls the rear wheels skidding value and adjusts the rotational speed of the front wheels accordingly.

During the simulation tests, the tractor is braked by the external devices generating the force countering movement of the tractor. This force was increased until the full skid of the rear wheels, and subsequently reduced to zero. Then the wheels have regained traction and the tractor moved forward. The tests were repeated for the system with mechanical switching on of the front axle drive and the system with a hybrid drive.

The simulation results are presented in Fig. 7. The chart on the left side presents the relation between the load of the tractor L and skidding of the rear wheels σ for different variants of the system operation. The second chart presents the load moment of the engine during the tests.

Curve no. 1 is the load force, imposed in the analysis, the rest present the relations of the rear wheels skid over time. Course no. 2 is the run of the tractor without switching on the front axle wheels. Along with an increase of the load, the skidding raises until reaching the critical value. The wheels start to spin in place and are unable to transmit effort that is more propulsive. Curve no. 3 presents the course of skidding of the rear axle wheels for the vehicle with the added front axle in classical drive. The tractor starts moving with the rear axle drive. The skidding starts to raise. After reaching, a certain value (15%) the front axle is being added. Skidding of the rear axle is decreasing, and then starts to raise again. During braking at the 10% of skidding, the front axle drive is switched off. There is again an increase in skidding of the rear wheels. The system is able to implement the full force of the towed weight provided in the test (curve no. 1). The forth curve presents behaviour of the system for the discussed hybrid drive. The system is equipped in a regulator, which changes transmission in the front axle so as to maintain skidding in the optimal conditions. Due to utilisation of an electromechanical transmission, we are able constantly to control the course of skidding in order to obtain an optimal towing force. The engine load chart shows that the engine load moment for the hybrid drive has a less sever course.

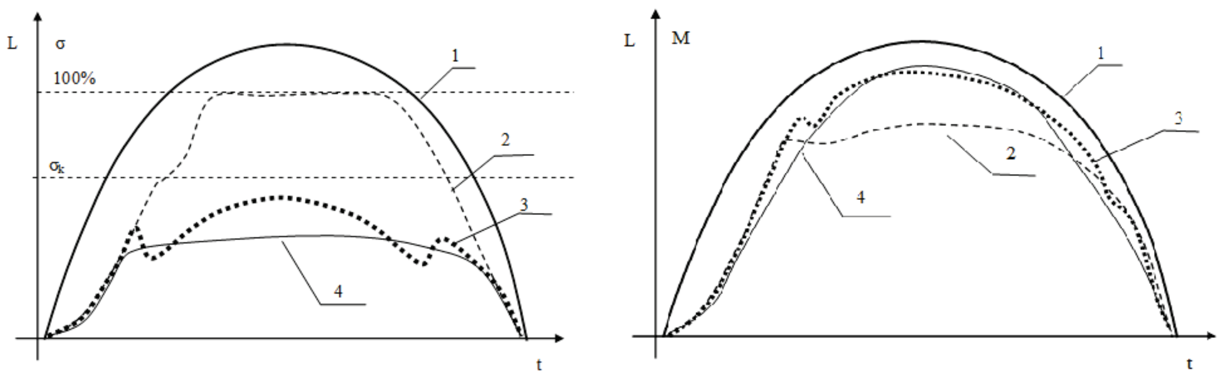

Fig. 7. Results of the simulation analyses of the tested tractor model

7. Conclusion

The presented hybrid tractor solution is characterised with the following features:

1. It enables controlling the driving system in such a way, so as to provide the best possible traction properties of the tractor.
2. It creates better possibility of control of the distribution of the propulsive effort between the axles and improves effectiveness and work efficiency of the tractor in a broad range of the load and changing terrain conditions, despite extension of the chain of power processing.
3. The proposed system characterises with a high flexibility, which enables it to adjust to changing work conditions.
4. Additionally, electric engine and storage cell allows driving in enclosed spaces, such as cattle shed or barn, without emission of fumes.

The concept of construction of hybrid tractors (multi-source) with dividable drives of the front and rear axles is an issue promising from the point of view of work effectiveness. It is in compliance with the concept of precision agriculture aiming at improvement of work efficiency and precision through electrification of the machines.

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