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Model-based efficiency evaluation of combine harvester traction drives

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As part of the research the drive train of the combine harvesters is investigated in detail. The focus on load- and power distribution, energy consumption and usage distribution are explicitly explored on two test machines. Based on the lessons learned during field operations, model-based studies of energy saving potential in the traction train of combine harvesters can now be quantified. Beyond that the virtual machine trial provides an opportunity to compare innovative drivetrain architectures and control solutions under reproducible conditions. As a result, an evaluation method is presented and generically used to draw comparisons under local representative operating conditions.

Key words

Combine harvester, traction drive, efficiency, operation profile, simulation

Cost-optimized traction drives in combine harvesters have led to the point that their efficiency potentials are not fully utilized (Anderl 2013). The increasing trend in research and development for electric drives (Gallmeier 2009) shows, in addition to their simple controllability, also a focus on development activity regarding to optimize processes through more easily realizable adjustments (Wöbke 2014) and fuel economy (Götz 2013). In the light of the "Europe 2020 targets" of the European Union (Europäische Kommission 2015) and the fact that operating costs of machines largely depend on fuel, this trend is driven by both politics and customers. However, there is currently a need to optimize existing hydraulic and mechanical drive systems and furthermore to raise as yet unused energy saving potential, due to long payback periods of electric drives (Gallmeier 2009) and the lack of expertise in workshops (Karner 2011). These systems have mainly been established because of the possibility of resolved construction, their simple controllability and the competitive price in the market of mobile machinery. The model-based efficiency evaluation offers the possibility to evaluate individual drive concepts in virtual experiments already during the development of machines. Therefore, it is possible to directly compare current and innovative solutions within reproducible conditions. In order to compare these solutions, a valuation method is necessary, which provides solutions who cope with the requirements of the optimization variables efficiency and performance, id est train solutions who are based on the mode of operation of the machine.

Operation profiles as a basis for determining energy saving potential

In order to evaluate mobile machines in the overall context of their task spectrum, so called "operation profiles" are needed. They divide the overall machine usage into subtasks which are shown as time shares. These profiles can be used, with detailed knowledge of the system, to quantify goal-oriented energy saving potentials on a process, machine and component level. Components with for example high power dissipation but very small percentage of time during the operation profile provide

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little potential for improving the energy performance of a machine (Fleczoreck 2011). Since 2010 detailed researches about the load and power distribution of combine harvesters take place at the Institute of Agricultural Engineering at the University of Hohenheim (Müller 2013b). The gained load spectra and operation profiles of the two test machines "Claas Lexion 470 Montana" and "Claas Lexion 750 Montana" can now be used to validate the traction drive models. The engineering tool "AMESim" by Siemens is used to build these models. Figure 1 shows an example of an operation profile of a test machine during the harvest 2014 at the "Schwäbische Alb". The recorded data covers a total field usage of 110 ha during the harvest. Due to the structure unloading happens on the field's side line. Because of bad weather and rain causing frequent interruptions during the harvest, stand and transfer time are higher than expected. The subtask "standing on street" includes, in addition to the actual downtime, also the time to connect and disconnect the cutting unit, as well as settings for when the cutting unit is not running. Settings while the unit is running such as settings regarding the crop are ascribed to the subtask "standing on field". If the time shares are combined according to the convention of KTBL (2012) into execution time, transfer time, waiting and set-up time, a good agreement to the survey conducted by the DLG for usage of combine harvesters during the harvest of 2012 is shown. The data includes 115 combine harvesters with a total harvest area of 45,000 ha (Häberle 2014a). However, this rough subdivision permits no conclusion about the actual subdivision of execution time and therefore it should be used only for comparison purposes.

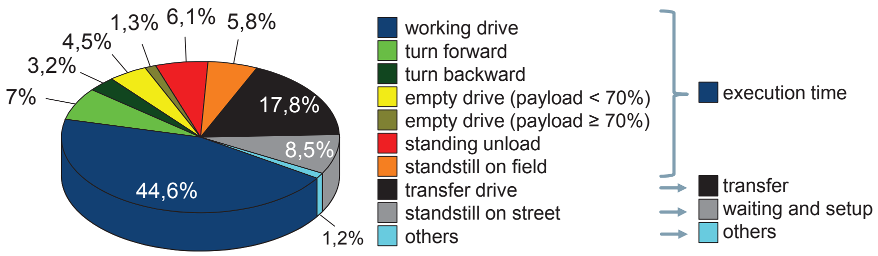

Figure 1: Operation profile of test trial combine harvester "Claas Lexion 750" during the harvest of 2014

The operation profiles of the test machine are already calculated by an automatic classification of the measured date during the operation. For that, the data of the machine CAN bus, the engine CAN bus and an additional installed measuring CAN bus is evaluated in real time. Thus, each time stamp of the measurement plot is assigned to a subtask of the combine harvester. Out of the data generated load spectra are divided according to tasks and offer thereby a deeper understanding of systems and processes. Through recombination of these load spectra other region-specific application profiles are represented by the weighting of their time shares (Müller 2013a). Thus, the model-based efficiency evaluation is not directly coupled to measurements and can also provide information about other regions without further field tests.

Method for model-based efficiency evaluation of mobile machines

The model-based efficiency evaluation of mobile machines can basically be divided into two methodologically distinctive areas; the simulation of representative operation points and the simulation of complete operation cycles. The comparative efficiency evaluation based on operation classes is particularly suitable for machines with high dynamic rates in motion and load behaviour (Sturm 2012). For representative evaluations other approved reference cycles are required. Typical examples out of the field of mobile machines are the Y-Cycle of wheel loaders and the 90° trench cycle of excavators. For machines with high amounts of time at quasi-stationary operating points in their operation profile, simulating representative operating points provide significant advantages in the field of model construction and validation. Currently there are no reference cycles especially for combine harvesters. The reason is mainly due to enormous variation of parameters that affect the movement and load behaviour of combine harvesters. Particularly field size and shape, stocking density, material moisture, soil moisture and soil type, topography, driving strategy and farm-field distance are to be mentioned. The simulation of individual operating points has the advantage that no separate cycle for each region and every type of application has to be worked out. It is rather sufficient to adapt the weighting of time shares to every load and performance point according to the application profile and regional situation in the overall machine evaluation.

Mutschler (2008) recommends based on an example of a wheel loader, a method of efficiency evaluation that illustrates cumulative the full load efficiency over the vehicle speed, weighted by the percentage of times shares out of the speed spectrum. Figure 2 shows the method in detail. The first step ① is to simulate the full load efficiency of the examine drive train with a validated model. The second step ② includes determining and setting the speed spectrum for the mobile machine which are to be analysed. Afterwards ③ the calculated efficiency for each simulated speed is weighted with the frequency of the speed spectrum. In the fourth step ④ the weighted efficiency is now shown cumulated over the speed.

The procedure is shown in equation 1. The running index i denotes the classes of the speed spectrum:

$$\eta_{kum,Volllast} = \sum_{i=1}^{m} \eta_{Volllast,i} \cdot \frac{t_{v,i}}{t_{v,ges}} \qquad \text{(Eq. 1)}$$

As a result of this evaluation, the maximum cumulative representation can be used as a comparison point. The evaluation allows to compare individual drive- or control solutions regarding to their efficiency for specific work task. Furthermore the weighted efficiency shows the energy saving potential of individual drive solutions in relative comparison to each speed range. Although a higher maximum value of the cumulative efficiency indicates that a drive for the examined task is in principle more suitable, this doesn't imply that it's the optimal solution for the complete speed range.

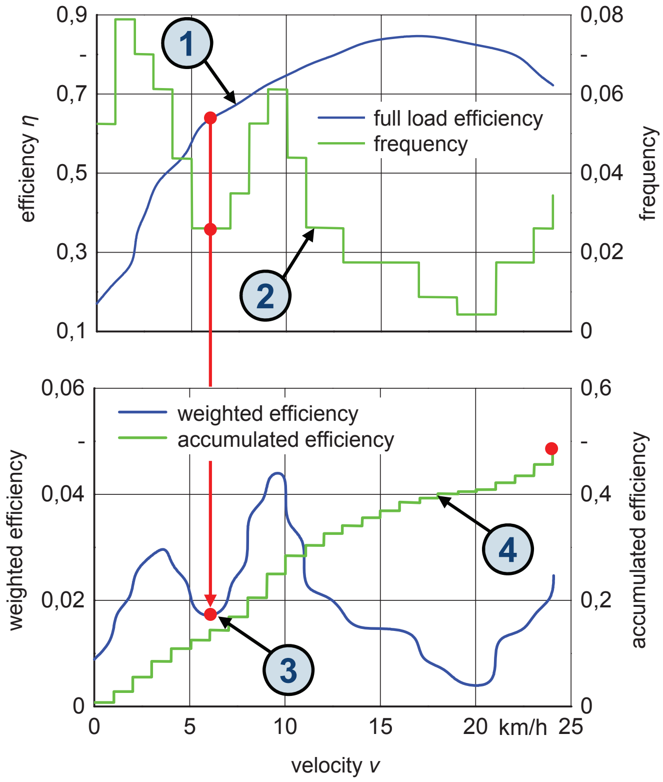

Figure 2: Method for efficiency evaluation by speed-dependent weighting of quasi-stationary full load points (according to Mutschler 2008)

Discussion of the method of evaluation for combine harvester traction drives

The advantages of the evaluation method are obvious according to Mutschler:

- The virtual machine test is used as a tool for efficiency rating. It allows innovative concepts, which don't exist as real drives, to be compared among reproducible conditions. Efficiency relevant work areas meaning areas with high percentage of time are given a special consideration by the weighting with the speed collective. In this way an analysis among equitable conditions is possible.
- The simulation of quasi-stationary operating points for the efficiency evaluation offers versus the transient calculation significant time saving potential in the calculation and validation. On the one hand only steady states and no transitions are considered. On the other hand the transient simulation assumes an exact replica of the control algorithms and system dynamics. So an exact knowledge of the system is for a sufficient and accurate picture of the real system fundamental. Furthermore by setting up a matrix of operating points through a single quasi-stationary simulation of these points, a rating for different collectives weighted with their own times shares is possible. However a transient simulation only considers the sequence of load cycles with an additional expenditure, as discrete time signals and not just individual operating points are required. Because of the very long simulation times this type of efficiency evaluation can be well used for individual machines but not for a wide application across multiple machines.

The speed, as an easily measurable size, offers a wide application of the method. Although combine harvester traction trains are by the high proportion of quasi-stationary operating points in their application profile predestined for this kind of efficiency evaluation, they show unique characteristics among other mobile machines, which are not considered yet. Combine harvesters experience additional payloads of more than 40% to their usual weight. Also performance for difficult harvesting conditions must be maintained. So harvester traction drives are designed for worst-case scenarios like a pitch drive with a full grain tank on soft ground. Therefore, the load spectra of harvester traction drives are characterized during normal conditions by high time shares in partial load operation. For a fair efficiency evaluation of usage, it's important to account not only the full load operations but especially the partial load operations. In addition to consider not only the speed-dependent evaluation of quasi-stationary full load points, as proposed by Mutschler (2008), but also to factor in the load-dependency of the efficiency, an extension of the evaluation method is necessary.

Extension of evaluation method

In order to consider the partial load shares, a load-dependent level is added to the method of Mutschler. For each speed level out of the spectrum a typical load distribution is simulated. The load distribution can be both measured and taken out of virtual load collectives or in the easiest way represented as single load points. Within a speed level, the model-based calculated efficiencies of the individual load points are weighted with the times shares and added up over the load. Analogue to Mutschler in the second step the cumulative efficiencies of each speed level are added up with every time shares of the speed collective over the speed. The addition of cumulative efficiency to the dimension of the load is expressed in equation 2:

$$\eta_{kum} = \sum_{i=1}^{m} \left(\sum_{j=1}^{n} \eta_{Last,j} \cdot \frac{t_{Last,j}}{t_{Last,ges}} \right)_i \cdot \frac{t_{v,i}}{t_{v,ges}} \qquad \text{(Eq. 2)}$$

The extended method of evaluation is divided into the following steps:

1. Simulation of quasi-stationary operating points is used to calculate speed- and load-dependent efficiency of the traction train. These predefined quasi-stationary partial load points are approached and analysed in the model for also predefined levels of speed.
2. Determination and definition of load- and speed-spectra for the task to be analysed
3. a) Weighting of the calculated efficiencies with the time shares of the load collective and summing up within a level of speed
   b) Weighting of the calculated sums of individual speed levels with the time shares of the speed collectives
4. Cumulative representation of load- and speed-weighted efficiencies

By summing up the weighted efficiencies of the load-/traction force and speed, efficiency relevant operating points are especially considered during the evaluation, because time shares from representative measured or virtually generated speed- and load spectra are factored in within the weighting. The advantage of this method compared to the evaluation based on the performance spectra of the wheel hub is that representative operating points composed out of speed and traction can be set up in the model. The simulation model briefly described in the following replaces the driver's pre-set speed with a PI-controller. The traction forces are either impressed directly or by a traction-slip model. One operating point in the performance spectrum represents theoretically a variety of possible operating points with different system settings which result from the multiplication of various traction forces and vehicle speeds. These points can't be represented with the existing model structure as defined operating points are required. For each operating point within the hydrostatic drive model there's a defined swivel angle, rotational speed and pressure.

Exemplary application of the extended model-based efficiency evaluation

The following compares two typical control solutions of hydrostatic drives for combine harvesters. The mechanical part of the traction drive and the hydraulic circuit remains unchanged in both classes. Therefore, only the impact of the changing control is evaluated on a comparable basis. The model's structure is realised with the simulation software AMESim by Siemens. The characteristic of the diesel engine transmits the retrieved performance through a pump-splitter gearbox to the hydraulic pump which connects with the hydraulic motor in a closed circuit. The hydrostatic models are equipped with validated efficiency characteristic diagrams. The losses of pressure in pipes and hoses are displayed with appropriate loss models. The hydraulic motor moves the wheel hubs via a mechanical two-range gearbox, a locking differential and a planetary gear drive. Through the chassis model, loads from the vehicle's longitudinal dynamics, the driving resistance and the traction-slip-behaviour can be simulated. Figure 3 shows the schematic structure of the validated model.

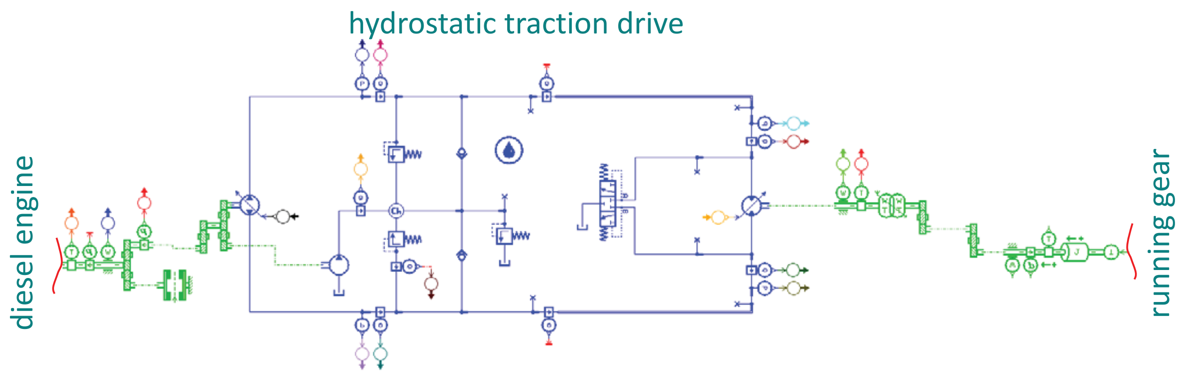

Figure 3: Schematic model of a combine harvester traction drive in AMESim

The simulation compares a pure follow-up adjustment of a primary adjustment with a pressure-dependent secondary adjustment. By using the secondary adjustment, the hydraulic motor is operated at reduced displacement which increases to the maximum volume starting at the impressed pressure.

The weighting of efficiencies for the speed-spectrum of a working-drive is taken out of the dissertation of Fleczoreck. It is based on the evaluation of telematics data from a machine fleet at the wheat harvest (Fleczoreck 2013). A characteristic of the working-drive is the high proportion of time marked in the main working range between 4 and 8 km/h. For load requirements, traction forces in the plane are assumed with an empty, half full and fully loaded grain tank on soft soil. These are weighted equally. So the sum of efficiencies weighted by load shares represents in this simple approach the average efficiency of these three load points. Figure 4 compares the efficiencies of the pure follow-up adjustment, weighted with the times shares of the load distribution, with the primary adjustment

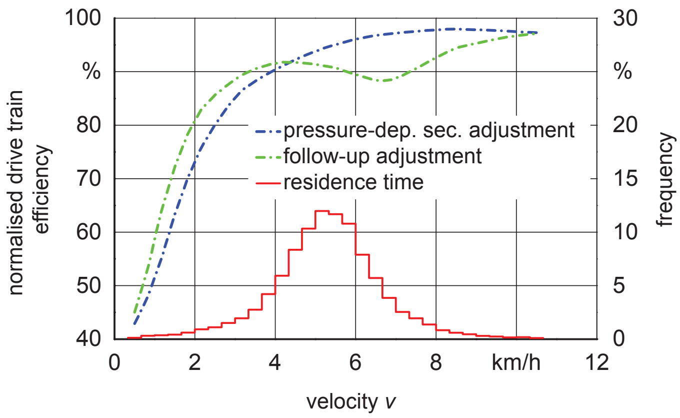

Figure 4: Comparison between two control solutions for hydrostatic traction drives of combine harvesters with a speed-collective for an operating drive (according to Fleczoreck 2013)

including the pressure-dependent secondary adjustment. Within a low speed range between 1 and 4.5 km/h the pure follow-up adjustment shows clear efficiency advantages, since the hydraulic pump runs, due to the larger displacement of the hydraulic motor, at every point of speed on a larger swing angle. At 4.5 km/h, it's the more weighted main work area of the combine, the efficiencies of the primary adjustment with the pressure-dependent secondary adjustment is much better due to the smaller displacement of the hydraulic motor and the associated higher level of medium pressure. Figure 5 shows the calculated and averaged efficiencies over the class width of speed collectives weighted with the percentage of time. The weighted efficiency is shown cumulated over the speed.

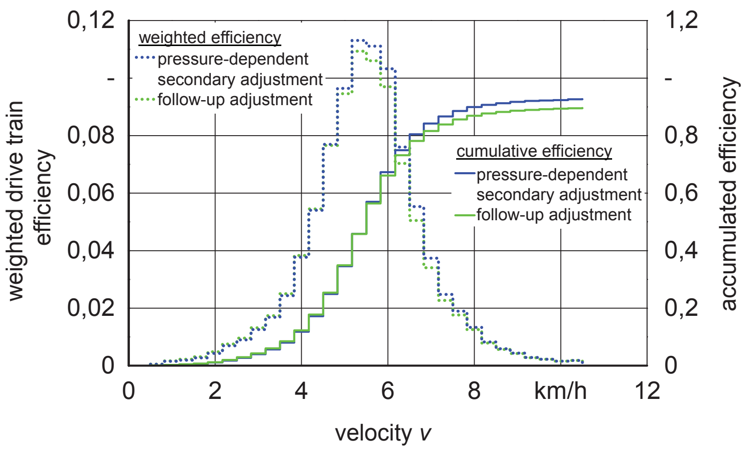

Figure 5: Weighted and accumulated efficiency for pressure-dependent secondary adjustment and the pure follow-up adjustment for a simulated operating drive of a combine harvester

In the terms of an energetic view and as a result of the model-based efficiency evaluation for the present dimension and rated subtasks of combine harvester a recommendation for the primary adjustment with pressure-dependent secondary adjustment can be pronounced. Within a direct comparison the cumulative efficiency of these control solution is 4.5 % higher.

Conclusion

The model-based efficiency evaluation has proved to be a powerful tool for reproducible comparisons between traction drive systems. Efficiency related advantages and disadvantages of individual solutions can be determined under representative conditions. By extending the method of evaluation with the load shares, combine harvester traction drives can be dimensioned better for their operating demands. Virtual drive- and field tests enable the identification of efficiency potentials already during the development process. In the future, innovative traction drive concepts and control solutions are evaluated and optimized with this extended evaluation method at the Institute of Agricultural Engineering at the University of Hohenheim.

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