Automatic end-of-line tuning for a motion inverter in agricultural tractors

Vincenzo Manzoni*, Mara Tanelli*, Sergio M. Savaresi* and Alberto Mangili‡

* Dipartimento di Elettronica e Informazione, Politecnico di Milano Piazza L. Da Vinci, 32, 20133 Milano, ITALY
‡ SAME Deutz-Fahr Group, Viale F. Cassani, 15, 24047 Treviglio (BG), ITALY

Abstract—End-of-line tuning is a crucial step for any mass-produced system endowed with automatic controllers. As a matter of fact, due to components tolerances and spreads in the production line, the controller tuning performed on a prototype system is never optimal on the final product. In many industrial applications, though, the end-of-line tuning is performed by human testers, and this does not always guarantee an objective assessment of the controlled system quality. This paper proposes a systematic way to design an automatic tuning procedure for an automatic motion-inverter in agricultural tractors, which allows to significantly reduce the costs of end-of-line tuning and to obtain a homogeneous maneuver quality in all vehicles. The effectiveness of the proposed approach is assessed on a prototype vehicle.

I. INTRODUCTION AND MOTIVATION

In industrial applications, when the final product is endowed with automatic control systems, a crucial step in the production line is the so-called end-of-line tuning. This phase is tailored to optimize the controller parameters tuning to each final system, which is always somehow different from the prototype on which the controller was designed. This is even more important when the final product is a complex system, on which multi-domain sub-subsystems (e.g., electrical, hydraulic, mechanical, electronic and so on) have to work together, as it is the case in the automotive industry, [1], [2]. Very often, though, the end-of-line tuning is performed by human testers, and this does not always guarantee an objective assessment of the controlled system quality.

This paper proposes a systematic way to design an automatic tuning procedure for an automatic motion-inverter in agricultural tractors, which allows to significantly reduce the costs of end-of-line tuning and to obtain an homogeneous maneuver quality in all vehicles despite manufacturing spreads and components tolerances. The objective of the motion-inverter is to perform a fully-automated motion inversion, which takes the tractor from a forward speed of - say - 10 km/h to a reverse speed (not a-priori fixed), which corresponds to a fully engaged clutch. The device (reverser) used for the automatic motion inversion is an electro-hydraulic system, constituted by two clutches and driven by a Proportional (EVP) and by an on-off Directional Electro-hydraulic Valve (EVD). The control variables are the currents of these valves, while the measured variables are the input/output rotational speeds of the reverser, the engine speed and the wheel speed. The design of the motion-inverter control system (see e.g., [3]) is a non-trivial task, as it is difficult to find a good compromise between inversion duration (the complete motion-inversion task should be performed in the shortest possible time) and comfort (bumps and oscillations on the longitudinal speed must be minimized).

The methodology proposed herein is based on the following steps: (i) devise a rational way to evaluate the maneuver quality from measured data; (ii) relate the maneuver quality with the controllers parameters which need to be tuned by means of a sensitivity analysis; (iii) use this information to design the auto-tuning algorithm.

It is worth noting that the approach presented in this work, even though tailored to a specific application, has a validity which goes beyond the considered problem, as the aforementioned design steps constitute a working paradigm which can be applied in many different production contexts. To better understand and motivate the strong need to overcome the subjectivity of the end-of-line tuning procedure when performed by human testers, refer to Figure 1, where the corrections to the input current (which is a crucial parameter of the motion inversion controller) of the reverse clutches applied by two different experienced testers to 58 different vehicles are shown. As can be seen in Figure 1, the first tester (represented by empty squares) tends to maintain the current unchanged while the second one (represented by black diamonds) privileges to increase the current of the clutch. This clearly shows that different persons of course privilege different aspects of the maneuver, e.g., one might prefer a shorter maneuver even if less comfortable and so on, thereby leading to non homogeneous vehicles behavior. Note that, as the vehicle handling characteristics are often seen as a trademark of the single manufacturer, the ability of delivering vehicles with identical maneuverability features can be a key to achieve customers’ satisfaction and fidelization. Moreover, another significant advantage of the proposed approach is that of reducing the industrial costs associated with end-of-line tuning. Consider that the tuning is now performed by an expert driver in a testing area separate from the production line. The overall procedure currently lasts about 20 minutes, which comprise both the time needed to bring the vehicle transmission oil to the needed temperature of approximately

Fig. 1. Corrections to the input current of the reverse clutch applied by two different testers to 58 different vehicles: empty squares represent the first tester and the black diamonds the second one.
40°C and the tuning phase.
The presented results are based on a joint work between Politecnico di Milano and the R&D Department of the SAME Deutz-Fahr Group (SAME, Lamborghini, Deutz-Fahr, Hürlimann, Adim Diesel and Deutz AG). This work has been developed on a Power-Shuttle transmission designed for low-power (80-100 HP) agricultural tractors.

II. SYSTEM DESCRIPTION

The overall scheme of the Power-shuttle transmission used in this work is displayed in Figure 2. Moving from left (engine) to right (wheels), notice that the transmission is mainly constituted by the reverser (oval box), the three main clutches (Low, Medium, High), and the synchro. The reverser and the three main clutches are controlled by the ECU, which drives the Electro-Hydraulic valves. Note that the reverser is cascaded with the rest of the transmission. Our work will focus on this part of the transmission only. As already said, the reverser is actuated by two Electro-Hydraulic valves: a proportional valve (EVP) and an on-off directional valve (EVD), which can assume three positions: F (Forward), N (Neutral) and R (Reverse). The measured variables are the input rotational speed of the shaft $\omega_{in}$ (which is equal to the engine speed), the output rotational speed of the shaft $\omega_{out}$ and the wheel speed $\omega_{w}$. The inversion system (see Figure 3) is constituted by two clutches (Forward and Reverse); each clutch is activated if the oil in the corresponding chamber is pressurized. The aim of the motion-inversion controller is to synchronize the activation and the de-activation of these two clutches, in order to provide smooth transitions from one clutch to another. This can be done by means of two Electro-Hydraulic valves: the directional valve (EVD), which is a 3-positions (Forward, Neutral, Reverse) 4-ways on-off valve; this valve is used to activate and de-activate the two-clutches; the second valve is a proportional valve (EVP), which modulates the pressure in the clutch chamber.

III. CONTROLLER DESCRIPTION

This Section is devoted to briefly illustrate the control system which takes care of the automatic motion inversion, as it is needed to understand how the design of the quality cost function. The overall controller is split into the open-loop phase, which controls the switch of the EVD valve and the open-loop modulation of the EVP during the first part (about 0.5 s) of the inversion and the closed-loop control of the speed of the output shaft of the reverser, using the controlled EVP. When the driver requires a motion inversion (this is done by manually activating a lever), the automatic control system takes full control of the maneuver, until the clutch in the opposite direction is fully engaged. A complete inversion (starting from a maximum speed of 13 km/h) usually takes 3–5 s. When the automatic inversion procedure starts, the first phase of the inversion algorithm is performed in open-loop (this phase takes about 0.5 s). During this open-loop phase the following actions are taken (consider, for example, an inversion from Forward to Reverse).

EVD: When the inversion procedure is triggered by the driver, the EVD - which was originally in the Forward position - is immediately switched to the Neutral position; as the EVP is closed, the pressure in the chamber of the Forward clutch immediately drops; when this pressure goes below (about) 4 Bar, the Forward clutch is completely disconnected (no torque is transmitted through this clutch). When the disconnection of the Forward clutch is completed, the EVD switches to the Reverse position, and the chamber of the Reverse clutch starts being filled. In practice, since the output pressure of the EVP is not measured, the EVD is switched from Neutral to Reverse not immediately after the pressure in the Forward clutch drops below 4 Bar, but after exactly 150 ms. This time window has been empirically estimated in order to guarantee the complete disconnection of the clutch in every working condition.

EVP: The open-loop strategy on the EVP is more complex than that on the EVD, since the EVP allows a continuous modulation, [4]. When the inversion starts, the EVP is immediately fully closed, in order to allow the quickest pressure drop in the Forward clutch. When the EVP is fully closed, the EVD is switched to the Reverse position, the EVP is reopened, in order to allow the rise of the
pressure problem in the Reverse clutch chamber. The open-loop control design problem is to find the best shape of the EVP current, in the 300–400 ms before the closed-loop control on the forward vehicle speed is activated. The open-loop EVP-current shape is displayed in Figure 4: when the EVD is switched into the Reverse condition (150 ms after the inversion is triggered), the EVP current is switched to its maximum value $I_{\text{max}}$ and kept at this value for 150 ms. Notice that - even if the EVP current is high during this time-window - the actual transmitted torque does not move the vehicle. In fact, the clutch chamber must be filled (when the Reverse clutch is activated, its pressure is very low, and it is partially empty). Thus, the best strategy is too keep the EVP current at its maximum value, in order to increase the pressure in the camber as quickly as possible. The time window of 150 ms has been computed in order to guarantee that the torque value corresponding to vehicle movement is not reached in every working condition. After 150 ms the EVP current is switched from $I_{\text{max}}$ to $I_{\text{limit}}$, that is the lowest value of the current that provides enough torque to move the vehicle, measured in different working conditions. This value of the EVP current is kept for another 150 ms; then the closed-loop algorithm is activated. Notice that this strategy has been designed to guarantee that no torque overshoot occurs (as it is cause of driver’s discomfort), at the price of a possible delay in reaching the movement torque.

In [3] the closed-loop part of the motion inversion control loop was also investigated. However, as the proposed auto-tuning procedure focuses on tuning the open-loop controller parameters, no further discussion is needed for the closed-loop control part. As a matter of fact, the closed-loop controller offers robustness guarantees which cope with components tolerances and production spreads, so that it is not object of end-of-line tuning.

IV. ASSESSING THE MANEUVER QUALITY

This Section aims at defining a cost function to assess the maneuver quality which takes into account both duration and comfort and - based on the available measured signals - outputs a quality index which classifies the performed maneuver together with the cost function value. For the purpose of this work, several maneuvers have been performed with the help of a driver who manually de-tuned the controller and who was asked to label each inversion as either good, medium or bad. We will show that the proposed automatic assessment process correctly matches the driver’s perception. To better understand the aim of the quality evaluation problem, consider the signals displayed in Figure 5. These signals represents the absolute value of the wheel speed (in [m/s]) of a tractor during an inversion. For both maneuvers, the inversion starts at a forward speed of 3 m/s and ends (after about 5 s) at a reverse speed of -3 m/s. In principle, the ideal behavior of the absolute value of the speed is V-shaped and composed by two smooth ramps, well represented by the dashed signal. Instead, the solid line represents a bad maneuver that differs from ideal behavior: the first part (braking phase) of the inversion is affected by filling-delays in the oil-chambers of the clutches, and this results in oscillations in the output speed. The result is an uncomfortable inversion. In fact, the human tester which performed the maneuver shown in Figure 5 as a solid line labeled it as bad.

Based on the previous description of the motion-inverter control system, it is clear that different design parameters concur to achieve a high quality maneuver. Specifically, the open-loop control is characterized by the following set of parameters:

- $I_{\text{limit}}$: this parameter is crucial, as a too high value of $I_{\text{limit}}$ implies that, when the open-loop phase is completed, the pressure in the clutch is higher than that ensuring movement, so that a strong deceleration causing discomfort is perceived by the driver. On the other hand, if $I_{\text{limit}}$ is too low, the clutch is not engaged after the open-loop phase and this results in a longer inversion;
- $\Delta t_1$: it is responsible for the clutch filling (its value impacts on the inversion in the same way as does $I_{\text{limit}}$);
- $\Delta t_2$: it represents the whole open-loop phase duration, estimated based on the hydraulic dynamics. It always showed to be appropriate in all the experiments, so that it does not appear to be crucial for the maneuver quality.

Based on these considerations, in what follows we concentrate on the automatic tuning of the parameter $I_{\text{limit}}$. However, note that all the following steps can be applied even in presence of multiple tuning parameters.

A. Inversion duration

We now describe in detail how to measure the motion-inversion duration, which is the first parameter that concurs to define the maneuver quality. The initial time instant at which the maneuver begins is easily assessed, as it is triggered by the driver’s action on a lever. As for the final time instant, instead, it must be determined based on the evaluation of the actual engagement of the clutch which is active at the end of the inversion (e.g., the Reverse clutch in a Forward $\rightarrow$ Reverse inversion). Clearly, an inversion maneuver can be requested at different vehicle speeds and - as the driver is allowed to accelerate during the maneuver - the clutch engagement can be achieved at a final speed different from the opposite of that at which the inversion began. Specifically, the clutch is said to be engaged when the engine speed $\omega_{\text{in}}$ equals the reverser output shaft speed $\omega_{\text{out}}$. Nonetheless, even during constant motion, the two are not perfectly equal due to measurement noise. Accordingly, we say that the clutch is fully engaged when the relation $\omega_{\text{out}} = \omega_{\text{in}} \pm 5\%$ holds over a time window of 300 ms. The 5% width of the tolerance zone has been chosen according to the experiments and to the transmission characteristics. Accordingly, it is difficult to correctly assess

![Fig. 5](image-url)
the maneuver quality independently of the initial and final wheel speeds if no action is taken to normalize the inversion duration. Thus, in order to obtain a significant and objective measure for the maneuver duration, it is necessary to express it in terms of normalized time; the final measure of inversion duration $\Delta_n$ is therefore computed as

$$
\Delta_n = \frac{d - \mu}{|\omega_{\text{init}} - \omega_{\text{end}}|} \left[ \frac{s^2}{m} \right] \quad (1)
$$

where $d$ [s] is the inversion duration, $\mu$ is the offset (which was experimentally identified based on all inversion tests), $\omega_{\text{init}}$ and $\omega_{\text{end}}$ [m/s] are the initial and the final wheel speeds, respectively.

### B. Inversion comfort

The second crucial attribute of a motion inversion is the driver comfort: the main cause of discomfort is due to large vehicle accelerations or decelerations which is mainly caused by a too large value of the open-loop parameter $I_{\text{limit}}$. In order to capture the effects of these bumps, we need to compute the best possible approximation of the longitudinal acceleration experienced by the driver based on the available signals, recalling that both the open-loop and the closed-loop phases are responsible for the overall discomfort of the motion inversion. Specifically, we devised a discomfort indicator which takes into account in a separate way the two main phases of the inversion, that is, the braking phase from the initial speed to zero, and the acceleration phase from zero to the final speed in the opposite direction. This decision can be motivated with reference to Figure 5: by inspecting this figure it appears that, in the first part of the inversion, the wheel speed shows significant over- and undershoots mainly due to a bad tuning of the open-loop controller parameter $I_{\text{limit}}$, while the oscillations in the second part of the inversion are less significant. However, also the second phase of the maneuver needs to be taken into account to provide a consistent discomfort assessment.

As such, the discomfort indicator in the braking phase is defined as

$$
c_b = \text{Var}[d\omega_{\text{w}}/dt]_{t \in \Delta t_1}, \quad (2)
$$

where $d\omega_{\text{w}}/dt$ is the numerically computed (and properly low-pass filtered) wheel acceleration and $\Delta t_1 = [t_{\text{ol}}, t_0]$ is the time interval between the time instant $t_{\text{ol}}$ at which the open loop control begins and the time instant $t_0$ at which zero speed is reached. Turning to the discomfort indicator for the acceleration phase, it is defined as

$$
c_a = \text{Var}[d\omega_{\text{w}}/dt]_{t \in \Delta t_2}, \quad (3)
$$

$\Delta t_2 = [t_0, t_{\text{end}}]$ is the time interval between the time instant $t_0$ at which zero speed is reached and the time instant $t_{\text{end}}$ at which the incoming clutch is engaged and the inversion is completed. The information yielded by the two separate discomfort indexes (2) and (3) is finally combined into a unique indicator which is a convex combination of the two components, that is

$$
c = \lambda c_b + (1 - \lambda) c_a, \quad \lambda \in [0, 1]. \quad (4)
$$

The optimal value for $\lambda$ in (4) has been tuned to $\lambda = 0.85$ by maximizing the separation between the clusters containing the good, medium and bad inversions as far as discomfort is concerned. The main motivation for compacting the discomfort information into a single variable is that the duration and the comfort quality indexes have to be optimized on-line with the auto-tuning algorithm. As such, reducing the optimization variables is a key both for efficiently solving the optimization problem and for being able of implementing it on the vehicle ECU, which offers limited computing power.

![Fig. 6. Classification of the motion inversions based on duration and discomfort. The maneuvers are also labeled according to the driver judgment: bad (red circle), medium (blue cross) and good (green x) inversions.](image)

To assess the quality of the overall two-dimensional quality index refer to Figure 6, which shows the classification of the maneuver comfort as function of the normalized inversion time. To confirm the consistency of the automatic quality assessment, the different maneuvers are indicated with the labels provided by the driver: bad (red circle), medium (blue cross) and good (green x), respectively. As can be seen by inspecting Figure 6, the proposed assessment of the maneuver quality correctly matches the driver perception and the different degrees of quality of the maneuver appear to fit in well separated clusters (see dotted boxes in Figure 6). Recall that, in Figure 6, the y-axis indicates the discomfort of the inversion; hence, Figure 6 allows also to highlight the intrinsic trade-off between the two conflicting requirements of short duration and small discomfort. As can be seen, however, all the inversions labeled as good need a certain value of duration in order to achieve good comfort attributes. This fact will be employed in the design of the auto-tuning algorithm.

### V. AUTOMATIC TUNING ALGORITHM

#### A. Sensitivity analysis

The next step towards the auto-tuning algorithm design is that of analyzing the sensitivity of the quality measure discussed in the previous section as a function of the tuning parameter $I_{\text{limit}}$. The results of this phase will provide the guidelines to select the most appropriate auto-tuning algorithm.

As such, several tests have been carried out, starting from low values of $I_{\text{limit}}$, which has been increased with steps of 3 mA. The overall range of variation for $I_{\text{limit}}$ was set to 40 mA, which has been derived from the analysis of the tuning phase performed by expert human testers (see also Figure 1). To take into account dispersions in the inversion maneuver quality, several tests have been performed for all values of $I_{\text{limit}}$. 

where $\alpha$ is the desired value of the discomfort index to be achieved by the auto-tuning procedure. The assumption based on which (6) was derived has been experimentally confirmed by the estimation of (5) for different clutches on different tractors. Based on this experiments, the final value for $\alpha$ employed to compute $\Delta I_{\text{limit}}$ was set to the sample mean of the estimates. The update rule (6) ensures a good speed of convergence, as it significantly modifies the value of $I_{\text{limit}}$ when far from the optimal one, whereas once close to the optimum - it allows a very fine adjustment, which leads to convergence with no oscillations. Finally, a termination condition for the algorithm must be chosen, which ensures a correct completion of the auto-tuning procedure. To define the best termination policy, consider again Figure 7: the spread in the discomfort index changes significantly with the discomfort value. Experimental data also suggest that it varies according to a uniform distribution. As such, the termination policy must take this into account, to adapt the termination condition to the chosen discomfort target value $c_t$. The support of the uniform distribution can be seen as a function of the discomfort index $c$. In fact, as already observed, the spread of the discomfort index as a function of $I_{\text{limit}}$ is non constant. Based on the measured data, both the sample mean $E[c]$ of the discomfort index samples for each fixed value of $I_{\text{limit}}$ and the length $l_s(c)$ of the associated uniform distribution support have been computed. Thus, the termination condition for the auto-tuning algorithm is defined as

$$|c - c_t| \leq \varepsilon(c_t) = l_s(c_t)/2.$$  

(7)

Hence, the tuning procedure will terminate when the error between the current comfort index value $c(t)$ and the target value $c_t$ is within half of the length of the $(c_t$-dependent) length of the associated uniform distribution support. As such, the overall auto-tuning algorithm can be summarized as follows:

1) define a discomfort target $c_t$, a maximum (normalized) duration $\Delta_{n_{th}}$ and compute a discomfort error threshold $\varepsilon(c_t)$ according to (6);
2) perform a motion inversion and compute both (normalized) duration and comfort based on (1) and (4);
   a) if $|c - c_t| \leq \varepsilon(c_t)$ in the last three inversions OR $\Delta_n \geq \Delta_{n_{th}}$
   go to Step 3
   b) else update the value of $I_{\text{limit}}$ according to (6) and go to Step 2
3) save and store the current value of $I_{\text{limit}}$.

Note that, to terminate the auto-tuning procedure, we require that the termination condition based on (7) is met in three successive inversions, in order to account for possible variations in the working condition which can affect the single maneuver. Furthermore, note that the threshold on the maximum duration has been experimentally set to $\Delta_{n_{th}} = 0.47\ s^2/m$.

VI. EXPERIMENTAL RESULTS

We now present and discuss some experimental results obtained with the auto-tuning algorithm implemented on the target ECU of the tractor. Specifically, the following cases will be analyzed: (1) auto-tuning procedure starting with different initial conditions, that is with initial values of the tuning
parameter $I_{\text{limit}}$, both significantly above and below the optimal value. This will confirm the convergence properties of the algorithm and the effectiveness and robustness of both the update law and of the termination condition; (2) auto-tuning procedure run with a different value for the comfort target $c_t$. The reliability of the algorithm in this case will witness the applicability of providing the final user a selector based on which to choose the inversion behaviour according to his/her current needs. As the target tractor will be extensively employed on orchards and vineyards, it is very likely that the available space for performing the inversion may change in different working conditions. As such, it is interesting to be able of providing the user an interactive way to privilege either comfort or duration. Let us start discussing case (1).

For this condition, the comfort target $c_t = 1.1 \text{ m}^2/\text{s}^4$ (recall that the threshold on the duration is set to $\Delta_{n_{th}} = 0.47 \text{ s}^2/\text{m}$). Figures 8 and 9 shows the results of the auto-tuning procedure with large initial values of $I_{\text{limit}}$. Specifically, Figure 9 shows (from top to bottom) the plot of $I_{\text{limit}}$, normalized duration $\Delta_n$ and discomfort index $c$. Whereas Figure 8 shows the time history of the initial (dashed line) and final (solid line) absolute value of the wheel speed. To better quantify the performance of the auto-tuning procedure, refer to Table I, where the value of $I_{\text{limit}}$, its distance from its optimal value $I_{\text{limit}}^{\text{opt}}$, (defined as usual on the basis of the expert testers indications) and the quality index measures are reported.

Consider now case (2). It is an unloaded vehicle with modified comfort target value, which was set to $c_t = 4.0 \text{ m}^2/\text{s}^4$ (the threshold on the duration is again fixed to $\Delta_{n_{th}} = 0.47 \text{ s}^2/\text{m}$). We expect that such a modification will lead to a final inversion behaviour which should privilege duration with respect to comfort. Again, this setting might be useful for the user to select when limited space is available to perform the motion inversion. Also in this case the proposed algorithm is very effective in reaching the desired discomfort target in a very limited number of maneuvers. As expected, in this case the duration decreases; this is consistent with the test objectives.

VII. CONCLUDING REMARKS

In this work a systematic methodology for the design of an automatic tuning algorithm for a motion-inverter in agricultural tractors has been presented. The proposed approach allows to significantly reduce the costs of end-of-line tuning and to obtain an homogeneous maneuver quality in all vehicles despite manufacturing spreads and components tolerances. All the performed experiments favorably witnessed both the correctness and the robustness of the proposed algorithm, thereby confirming its industrial applicability. Note, moreover, that now the auto-tuning can be performed in a fully automatic way, with an average number of 10 inversions per clutch, i.e., 2 minutes per vehicle, and without the need of an expert tester. As such, it can be done straight after the completion of vehicle production, which saves also the cost of both fuel and time needed to heat the transmission.

REFERENCES