Adaptive Park Brake Technology to Improve Stability of Wheeled Excavators

Davide Moser, Lorenzo Serrao and Giulio Ornella

Dana Mechatronics Technology Center, Via Zeni 8, 38068 Rovereto (TN), Italy

E-Mail: davide.moser@dana.com, lorenzo.serrao@dana.com, giulio.ornella@dana.com

Rocking is often observed in wheeled excavators while digging, which impacts driver comfort and precision. To minimize rocking, wheeled excavators need special axles with brakes at the wheel-end. The paper presents a new solution to use low cost in-board brakes achieving the same or better stability compared to wheel brakes. This is achieved by disconnecting one axle and braking it, while torque is actively applied on the other axle with a hydrostatic traction motor, to preload the driveline and keep the vehicle more stable. The system hydraulic circuit and the corresponding control algorithms are presented, as well as experimental results that prove the concept feasibility.

Keywords: Fluid power systems, mechatronics, excavator, driveline, control
Target audience: Mobile Hydraulics, Construction Machinery, Mechatronics

1 Introduction

This paper presents a new concept to reduce the rocking phenomenon observed in wheeled excavators while digging. This phenomenon significantly impacts the operator comfort perceived and the driver precision during digging phase, reducing the vehicle stability.

Field tests highlighted that the vehicle oscillations are caused by: mechanical backlashes between tire and brake; tire slipping and deformation; and shaft torsional deformation. These effects induce a dynamic load transfer that amplifies the oscillation perceived from the driver seat. This is depicted in Figure 1, while an example of oscillation measurements is shown in Figure 2.

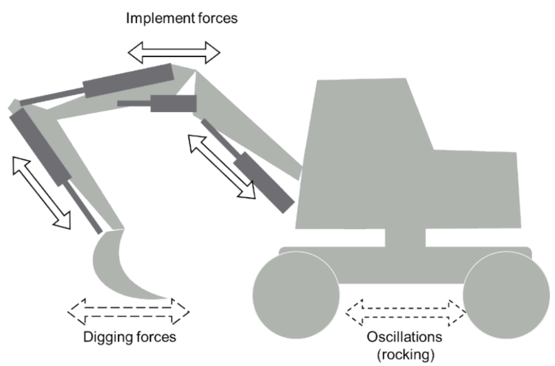


Figure 1: Vehicle rocking (oscillations) during digging

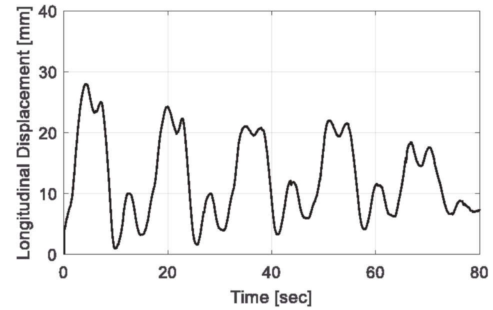


Figure 2: Experimental characterization of vehicle oscillation (longitudinal frame displacement) during digging

The brake system installed in the axles is very important for the overall stability characteristics. A typical off-highway axle provides several functions: structural support; drive torque transmission with speed reduction at the bevel set (differential) and at the wheel hub; service brakes; and park brakes. Service brakes are often based on multiple wet disc solutions, which can be installed at one of the following locations, shown in Figure 3:

- At wheel: the friction components act on the wheel hub (i.e. after the hub-drive reduction);
- Outboard: the friction components act on the axle half shaft, and are located close to the hub;
- Inboard: the friction components act on the axle half shaft, and are located close to the differential.

The solution with brakes at wheel is more expensive due to the larger amount of torque to be generated by the brakes, and more complex in terms of integration in the axle design. However, it is the only solution that provides an acceptable level of vehicle frame oscillation during digging, since the only deformable element between the brakes and the external environment is the tire. On the other hand, inboard brakes hold the inner side of the half shaft, but the vehicle/terrain forces can generate oscillation due to tire deformation and half shaft torsion.

The goal of the concept described here is to avoid this solution and instead use inboard or outboard brakes, while achieving equal or better stability performance compared to the wheel brakes. The concept and the testing results provided here are based on a vehicle equipped with axles using inboard brakes, and a hydrostatic transmission, based on centrally-mounted two-speed gearbox, with disconnection device for the front axle.

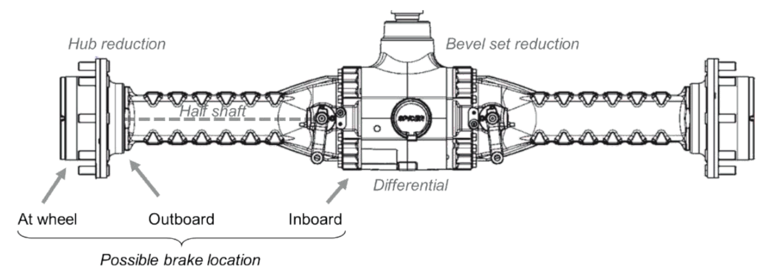


Figure 3: Off-highway axle and brake locations

2 Concept and system architecture

The Adaptive Park Brake (APB) is a mechatronic device that can be used to improve the stability of a wheeled excavator. It applies to a vehicle where one axle is driven, or equipped with a disconnect device if both axles are driven (as in most construction vehicles), so that one axle is disengaged from the traction during system operation. The APB function can be summarized as follows: while the vehicle is stationary and is performing a digging operation, one axle is disengaged, and brakes are applied on it; at the same time, the traction motor generates torque on the other axle. The motor torque opposes the brakes and thus overcomes the mechanical backlashes and shafts torsion by "preloading" the entire driveline and the tires. The result is a reduction of vehicle oscillations thanks to the elimination of backlash and deformation.

In the examples shown in this paper, the system engages the front brakes and actuates the hydraulic motor which is connected to the rear axle. The motor torque can be applied in either direction: pushing the powered axle towards the braked axle (compression preloading of the driveline, shown in Figure 4), or pulling it away (extension preloading of the driveline).

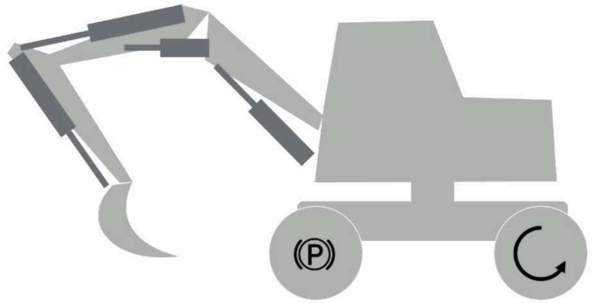


Figure 4: Basic idea of driveline pre-loading for stability

The motor torque generating the preload is not constant, but rather it is computed in real-time to stabilize the vehicle without reaching the limit of wheel slip on the terrain. The system is developed for a hydrostatic transmission, so the torque generated can be controlled by using the motor displacement or the pressure. Pressure control is preferred, for two main reasons:

- the variation of pressure can be faster than the actuation of displacement;
- controlling the torque via the pressure allows to implement the system even in drivelines where the motor is of the fixed-displacement type, or is equipped with a non-electronic displacement control (e.g. purely hydraulic automotive displacement control, or electronic control with hydraulic override).

A schematic representation of the system as implemented in a Dana prototype vehicle is shown in Figure 5. Through the use of sensors, the system state is identified, and an electronic control unit generates an appropriate set-point of torque to be applied at the motor.

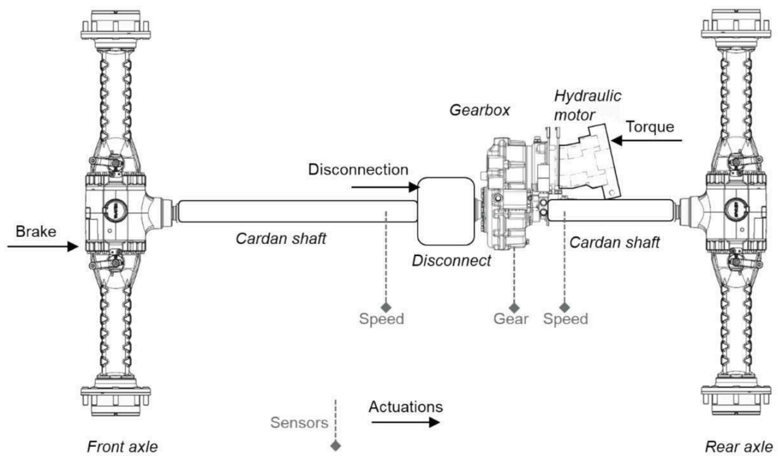


Figure 5: System architecture

3 Hydraulic circuit

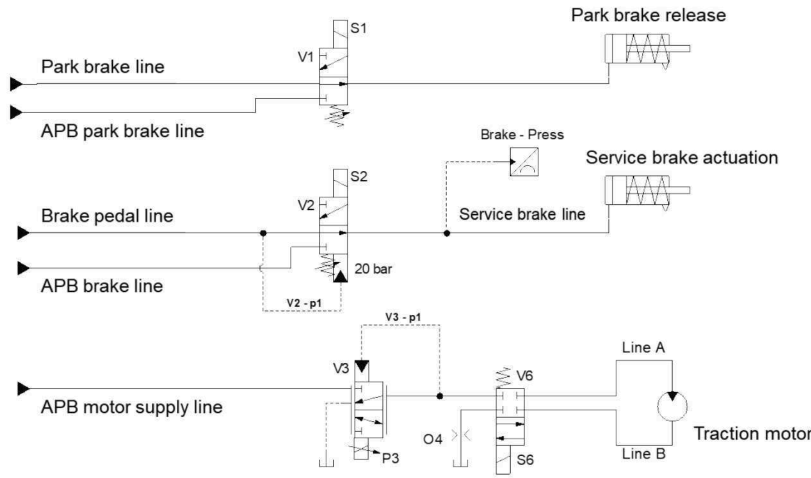


Figure 6: Hydraulic circuit for APB

The APB function can be realized using different circuits. The solution shown in Figure 6 implements the basic functionality of APB: release the standard park brake, apply the service brakes on front axle, apply pressure on the motor acting on rear axle, and ensure safe operation of the system (i.e. ensure that torque is not applied on rear axle without braking the front axle first).

Valve V1 is used to release the park brake: this operation is necessary because the system needs to apply torque at the rear wheels with the traction motor, and the front wheels are already subject to the service brake.

The system applies braking torque by generating pressure on the service brake line using valve V2. The brake pressure corresponds to either the APB brake line supply, or to the standard brake-pedal pressure. The switch between these two values is determined by valve V2: when actuated (by the APB controller), it applies the APB supply brake line to the service brakes; when disabled, instead, it ensures the brake pressure is at the value set by the brake pedal. If the brake pedal is actuated during APB operation, the pedal pressure acts on V2 via the pilot line V2-p1, and pushes V2 back to its rest position. Thus, the brake line receives the pressure from the brake-pedal line, overriding the APB brake pressure setpoint. This means that the driver always has the ability to stop the vehicle using the service brake pedal, independently of the APB status.

To apply the correct amount of pressure to the hydraulic motor, V3 is a continuous electrically-actuated pressure reducing/relieving valve, which sets the pressure value between zero and the power supply value, according to the control signal to solenoid P3.

To guarantee safe operation, pressure on Motor 1 can be applied by APB only when the brake line is pressurized with a pressure level sufficient to hold the vehicle still. This is achieved by measuring the brake pressure level with a sensor, and using the information in the controller to enable the actuation of solenoids S6 (for on/off valve V6) and P3 (for continuous pressure-reducing valve V3). Note that V6, instead of a simple on/off, could be a 3-position directional valve to determine the direction of traction motor actuation.

The time sequence of the APB operation is as follows:

i. Generation of pressure in brake line

ii. Release of park brake

iii. Generation of motor pressure

The supply circuit for the APB signals is shown in Figure 7. The circuit uses the standard pump that generates the power supply for the main hydraulic line, and a set of pressure reducing/relieving valves to generate adequate pressure levels at the different lines. The accumulator A1 is present to ensure an approximately constant pressure and flow to the APB brake line even in case of pump failure. The dynamic response of the pump and the accumulator system is such that the pressure in the APB motor supply line slows down the generation of pressure at the motor, creating a smooth torque actuation.

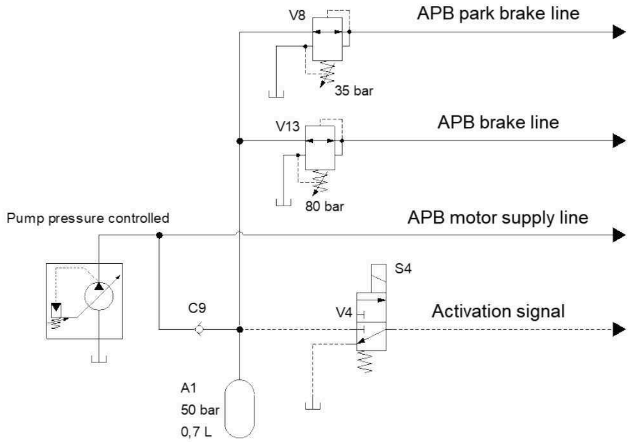


Figure 7: Supply circuit

4 Control strategy

The control system is composed of the following main functions:

F1) Safety supervisor: this is a supervisor layer that constantly monitors the APB operating conditions. In case of anomalous conditions, the supervisor disables the APB system in a controlled manner ("soft dump")

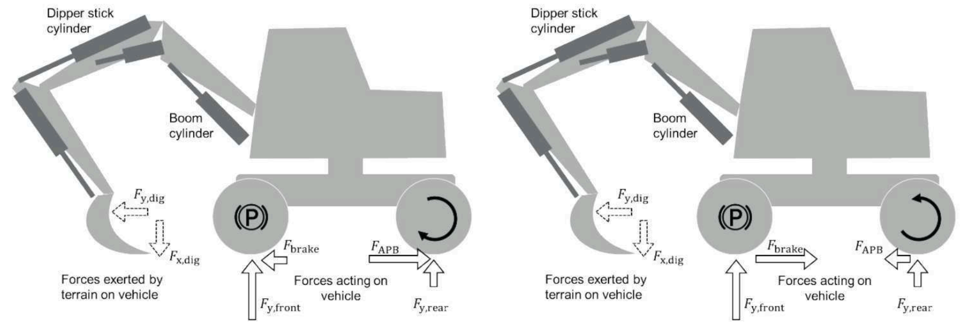
F2) Slip limit detection: this part of the algorithms detects the amount of friction at the ground/wheel interface and therefore the conditions of impending wheel slip. This condition depends on many factors, mainly: ground type; weather condition; presence of a limited-slip or lockable differential; pneumatic tire type, wear, and pressure; vehicle weight. This control is executed at APB activation, and it is corrected during operation by the function F3 (next point). From a practical point of view, the output of this function is the max torque T_{max} that can be applied by the motor without creating wheel slip, and is determined by continuously monitoring the available speed measurements.

F3) Motor torque setpoint: this value, T_{sp}, is generated as a value smaller than T_{max}. The difference depends on the type of ground (which is identified in F2, as it is strictly related to the value of T_{max}).

F4) Anti-slip: This function controls the tire slip, trying to maintain the tires in the condition of zero slip, by generating the torque T_{sp} with the motor. This is achieved by acting on the pressure of the motor line. The amount of torque to be realized depends on instantaneous operating conditions, for instance on the amount of load acting on the motor axle (which is variable during the digging operation). Thus, if slip is detected while applying the torque T_{sp} determined in F3, a new (reduced) setpoint is immediately applied in order to reduce the tire slip. The system learns the values of torque that produce more or less slip during operation and periodically updates F2.

The forces acting on the vehicle during digging operation are shown in Figure 8. The largest forces are those generated by the main actuation cylinders:

- Dipper stick cylinder, which generates a mostly longitudinal force that tends to move the vehicle frame forward (when the driver is digging, i.e. moving the bucket towards the cabin, as shown)
- Boom cylinder, which generates a force with a longitudinal component (same effect as above), and a vertical component that tends to move the front axle downward (increasing its vertical load) and the rear axle upward (decreasing its vertical load).



a) Reverse mode *b) Forward mode*

Figure 8: Operating modes

At the vehicle level, the longitudinal equilibrium is always:

$$F_{\mathrm{APB}} + F_{\mathrm{brake}} = F_{\mathrm{x,dig}}$$

where F_{APB} is the force generated, via the hydraulic motor, by the APB system; $F_{\mathrm{x,dig}}$ is the digging force acting on the bucket and due to the digging operation (it is time-varying and unknown); and F_{brake} is the force generated by the brake acting on the front axle. F_{brake} can be likened to a static friction force, which is not known because it can take any value between zero and the maximum brake force corresponding to the brake actuation pressure.

The system can be controlled using one of two control modes, which differ for the direction of the torque generated by the hydraulic motor.

In the *reverse* mode (Figure 8.a), the hydraulic motor pushes the vehicle backward, against the direction in which the boom would tend to move it. The force generated by the motor torque balances the sum of the digging forces and deforms the driveline recovering all backlash and elastic deformation; thus, $F_{\mathrm{APB}} > F_{\mathrm{x,dig}}$, which means that F_{brake} is negative (in fact, as shown, it is acting opposite to F_{APB}): the brake is balancing the driveline preload torque. When the rear axle is lifted (or the load on it decreases to a point that the tire starts to slip), the motor torque cannot be transferred to ground, which means the force becomes zero and the driveline preload disappears, so that backlashes appear again. However, the overall performance is still better than the standard vehicle without APB (i.e., rocking decreases). The advantage of the reverse mode is that the overall force opposing digging is high, being the sum of the APB and parking brake effects.

In the *forward* mode, the hydraulic motor pushes the vehicle forward, towards the boom, i.e. in the same direction as the vehicle would tend to move if not held by the brakes. Referring to Figure 8.b, the motor tends to rotate the rear tires in CCW direction, and to generate a force on the vehicle frame that is concordant with the digging force. This means the brake on the front axle must be able to keep the vehicle stopped acting against both F_{APB} and $F_{\mathrm{x,dig}}$, which may require a higher brake pressure. Compared to the reverse case, the APB system must generate a much smaller force F_{APB}, i.e. only the amount needed to overcome the backlashes, because anything more would effectively reduce the total amount of braking. Despite the higher braking pressure required, this strategy generates the best APB results, in terms of oscillation reduction, because the slip of the rear axle in instants of low vertical load does not nullify the driveline preload as in the previous case. For this reason, it was implemented on the vehicle prototype realized for experimental validation of the concept.

5 Experimental results

The preliminary tests and the implementation of control algorithm were realized using an internal proto vehicle, based on a Komatsu PW110 wheeled excavator. The front and rear axle were replaced by a Dana Spicer 212 steering axle. The hydrostatic driveline is composed by a 90-cc load sensing pump, a 110-cc bent-axis motor with electro-proportional control, and a Dana Spicer 367 shift-on-fly gearbox, which is a 2-speed mechanical transmission equipped with disconnect device. The hydraulic transmission is of the open-circuit type. Several sensors were installed to characterize the system behaviour: cable position sensor on rear blade to measure the longitudinal movements (with respect to the ground), engagement switch on gearbox and disconnect device, pressure sensors on hydraulic power and pilot lines, speed sensors on gearbox, motor and cardan shaft. A picture of the vehicle prototype is shown in Figure 9.

Figure 9: Experimental vehicle (driven by the first author)

Tests were performed in different conditions and using both the control modes described before as *reverse* and *forward*; as mentioned, the best results were observed with the *forward* mode. An example is shown in Figure 10, which demonstrates how the use of the system allows to reduce the longitudinal oscillations considerably. The amplitude decreases by roughly 50%, and the high-frequency oscillations disappear in the case with APB. For this reason, the comfort perceived by the driver is sensibly improved. The vehicle is much more stable during the digging operation, and this is clearly observed from the outside.

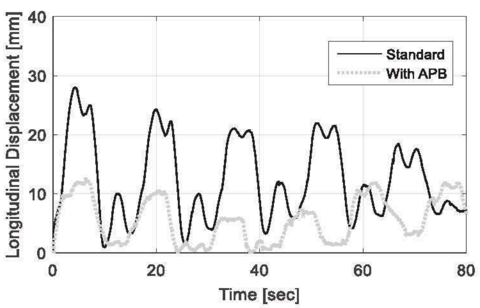


Figure 10: Experimental results (longitudinal frame displacement during digging)

6 Conclusion

The adaptive park brake system constitutes an effective solution for the rocking problem, based on innovative use of existing components via system integration and control. The experimental proof-of-concept demonstrate a visible and perceivable reduction of the oscillation while digging, which improves the operator comfort and precision. The system is currently under testing and future work includes further development towards production-intent design.