Technical note

Mechatronic Solutions for the Safety of Workers Involved in the Use of Manure Spreader

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Abstract: An internationally acknowledged requirement is to analyze and provide technical solutions for prevention and safety during use and maintenance of manure spreader wagons. Injuries statistics data and specific studies show that particular constructive criticalities have been identified on these machines, which are the cause of serious and often fatal accidents. These accidents particularly occur during the washing and maintenance phases, especially when such practices are carried out inside the hopper when the working bodies of the machine are in action. The current technical standards and the various safety requirements under consideration have not always been effective for protecting workers. To this end, the use of SWOT analysis allowed to highlight critical and positive aspects of the different solutions studied for reducing the risk due to contact with the working bodies. The selected and tested solution consists in a decoupling system automatically activated when the wheels of the wagon are not moving. Such a solution prevents the contact with the moving working bodies of the machine when the worker is inside the hopper. This mechatronic solution allowed to obtain a prototype that has led to the resolution of the issues related to the use of the wagon itself: in fact the system guarantees the stopping of manure spreading organs in about 12 seconds from the moment of the wheels stopping.

Keywords: manure spreader; safety; decoupler; mechatronic; SWOT analysis

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1. Introduction

The risk of injuries related to the use of agricultural machinery has always been of primary importance, as evidenced by the high incidence of accidents at work resulting from the improper use of agricultural machinery and equipment [1,2,3,4,5,6,7].

The aim of this work focuses on the needs, recognized at national and European level, to provide technical solutions [8,9,10,11,12,13] against the risk of crushing, catching and cutting during the use of self-propelled or towed manure spreaders. These are agricultural machines used to distribute manure or other materials over a field. Their use is fairly widespread in livestock farms, but it could be even more widespread in the future because of climate change that may require more organic matter inputs to the soil over vast areas of the globe [14,15,16].

Specific sector studies and surveys [17,18,19,20,21] identified particular constructive critical issues on some machines currently in the market and/or already in use that involve the above-mentioned risks and determine the occurrence of a significant number of serious or fatal accidents.

The technical standards in force concerning this type of machine or the risks arising from its use have not always been effective for the protection of workers. A critical point often observed regards

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the washing and maintenance operations carried out by operators located inside the hopper when the working bodies of the machine are in motion.

In European and international literature, statistical data regarding accidents during use and maintenance of this type of machine are available. In France, between years 2002 and 2012, 8 injuries were recorded by IRSTEA (Institut national de Recherche en Sciences et Technologies pour l'Environnement et l'Agriculture) during the use of manure spreaders, of which three were fatal; the common cause of these accidents is the trapping of the operator between the spreading organs [19]. Moreover these accidents occurred during three different stages of work: cleaning, maintenance and unlocking the rotor. In Germany, between 1998 and 2008, 12 fatal accidents were recorded by LSV-SpV (Spitzenverband der landwirtschaftlichen Sozialversicherung), during the use of this machine. The common cause for eight of these accidents was the same: catching of operator between the spreading organs. These accidents occurred during various machining steps: 3 during cleaning, 2 during maintenance, 2 during unlock and 1 during a non-defined working phase. Accidents occurred in Italy during the use or maintenance of such equipment and recorded by INAIL (Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro) [22, 23] were a total of 17, all occurring between 2002 and 2015: 9 fatal accidents were caused by the overturning of the tractor to which the manure spreader was attached, due to the excessive slopes of the ground; 2 cases with the same dynamics and tragic outcome, but involving self-propelled spreaders; 2 cases (of which one fatal) occurred during the replacement and maintenance of the trailer wheels; 2 fatal cases were due to the crushing caused by the not inserted handbrake; 2 cases (of which one fatal) occurred during the rotors maintenance. Other data are available outside Europe: in Ontario (Canada) 6 fatal accidents due to manure spreaders were recorded by CAIR (Canadian Agricultural Injury Reporting) between 1990 and 2008; in California (USA) OSHA (Occupational Safety and Health Administration) recorded 1 fatal accident in 2015, during the cleaning operation.

Since 2009 the Health and Safety Office of the French Ministry of Agriculture and Food started various feasibility studies with regard to the improvement of safety of manure spreaders during the washing operations, at the aim of a revision of the harmonized Standard EN 690 + A1 (Safety of Manure Spreader). The results of these studies confirm both the possibility of cleaning the moving parts of the machine, such as rollers and conveyor belt, without the need for the operator to be inside the load compartment while carrying out this operation, and the possibility of providing the machine of a system that prevents the movement of working bodies when the machine itself is not in motion (steady wheels), thereby eliminating the risk of trapping the operator inside the rotating parts [24].

2. Materials and Methods

At the aim of select the best solution in terms of risk reduction, the SWOT analysis (Strengths, Weaknesses, Opportunities and Threats analysis) was applied to different solutions proposed by different Authors [19,20,21].

The SWOT analysis is a support analysis that responds to a need for rationalization of decision-making processes. In practice this type of study is a logical process, originally used in business economics and then applied to other areas, which makes it possible to make systematic and useful information collected about a specific theme. The amount of data collected with this system is crucial to outline the policies and lines of action that result from enhancing strengths and reducing weaknesses in the light of the opportunities and risks that normally arise from the external situation.

The advantages of this analysis are: depth analysis of the context in the definition of strategies; verification of matching between strategy and needs improves effectiveness; it allows for consensus on the strategies (if all parties involved in the intervention participate in the analysis); flexibility.

The disadvantages of this analysis are: the risk of subjective procedures by the evaluation team in the selection of the actions; can describe reality in a way too simplistic; if there is no implementation in a context of partnership there is a risk of discrepancy between a pragmatic scientific and political plan.

The mechatronic solution resulted the system that minimizes the risks for the operator's safety. From a mechatronic point of view, the decoupler consists of a magneto-mechanical mechanism that prevents motion to all moving parts of the wagon if the machine is not in motion. The reset of the movement is possible via a hold-to-run control applied in a secure area of the wagon itself.

The basic elements of the system are:

- wagon wheel movement detectors (wheels);
- a motor disengagement device (clutch);
- a torque limiter to limit the torque during overloads;
- a programmable logic controller (PLC);
- a man-made command for manual resetting of conveyor and distributor systems, located in a safe area;
- a hydraulic distributor or a solenoid valve for conveyor control.

Considering the existing electromagnetic clutches on the market, there is little availability of clutches suitable for electric voltages that correspond to those of the tractor (12 V), and above all suitable to withstand the dissipation of rotations with the torque values of the machines rating. The minimum data for the correct sizing of the clutches are very variable. The only information currently available are shown in Table 1.

Table 1. Data for clutch dimensioning.

Rotation speed[1] (rpm)	Transmitting torque (Nm)	Supply voltage
540	2200	12
1000	1600	12

[1] depending on the model

The variability of the characteristics of the wagons on the market is very wide; other variables are to be considered that would not allow a fair uniformity of adoption. Possible variables are due to:

- transmission shaft type below the loading platform;
- geometric shape;
- length;
- diameter;
- mass of the entire axis;
- any vibrations and/or movements.

Giving good for the likelihood of the drive shafts with cardan shafts for transmission of motion that are commonly used on agricultural vehicles, we have come to the conclusions described in the following paragraph.

3. Results

Conduct SWOT analysis (Table 2) shows how the application of the decoupler, also in function of detected weaknesses and threats, is a mechatronic solution applicable on great scale and which ensures, at the same time, an optimal result to remedy the safety problems related to this machine. A similar solution has recently been applied to other machines [25].

Table 2. SWOT analysis regarding the decoupling device.

Strengths	Weaknesses
Working organs stopped during cleaning and maintenance operations.	High component costs. High installation, assembly and setup costs.
Possibility of a manual reset in a safe area.	Necessity of regulatory transposition and any objections by manufacturers.
Possibility to break the movements of the working bodies with the aid of the tractor hydraulics.	Difficulties in adapting machines already on the market and in use.

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Flow solenoid valve that facilitates the adjustment of the speed of the conveyor belts.	Not easily adaptable by small/middle builders.
The rotating sensor detects the wagon's motion.	Need to adjust the speed of the conveyor belt.
Minor space displacement in case of downstream positioning of the clutch.	Possible malfunctions and / or breaks of the various components.
Possibility to break the movements of the two transmission organs.	With clutch located downstream of the hydraulic unit, provide a stop mechanism for conveyor belts (risk of injury of the lower limbs if the chains remain in motion).
Electromagnetic clutches that can be powered by the electric voltage (12 V) of the tractor.	Requirements of a separate hydraulic circuit if hydraulic clutches are used.
Less expensive, less bulky and easier to install and integrate electromagnetic clutch.	Low availability of 12V clutches.
Separate tractor/wagon hydraulic circuits.	The need for a torque limiter.
Difficult system inactivation.	The need for a programmable logic controller (PLC).
	Possible conflicts with electronic regulation systems.
	Not easily inserted in the ISOBUS technology.
Opportunities	**Threats**
Robust, durable and reliable system.	Procedural distortion in the production line.
Polyfunctional system for other types of machines (e.g. round baler that, together with manual reset, must only engage the machine when it is in motion).	Request for specialized technical personnel.
Improved safety.	Possible rearmament of the system with the help of a second person or thing that keeps inserted the old-to-run control.
Possible rearming of the motion of the working bodies by means of hold-to-run control.	High risks if the movements are not disrupted.
Probable reduction of sensor costs.	Sensors relatively fragile.
	Hydraulic pump driven by the PTO.
	The second stop mechanism makes the total costs rise.
	In the absence of a hydraulic unit, the application of a circuit causes considerable additional costs.
	PLCs and other microcomponents make the set relatively expensive and complex.
	Total costs unavailable by all manufacturing companies.
	Field operational problems and possibility of frequent blockages due to clogging.

A decoupling system (Figure 1) has been designed and developed thanks to the cooperation of the company Ren Mark Snc (San Polo d'Enza, Italy). A prototype of the system was applied to a towed model of manure spreader (Ren Mark RP140).

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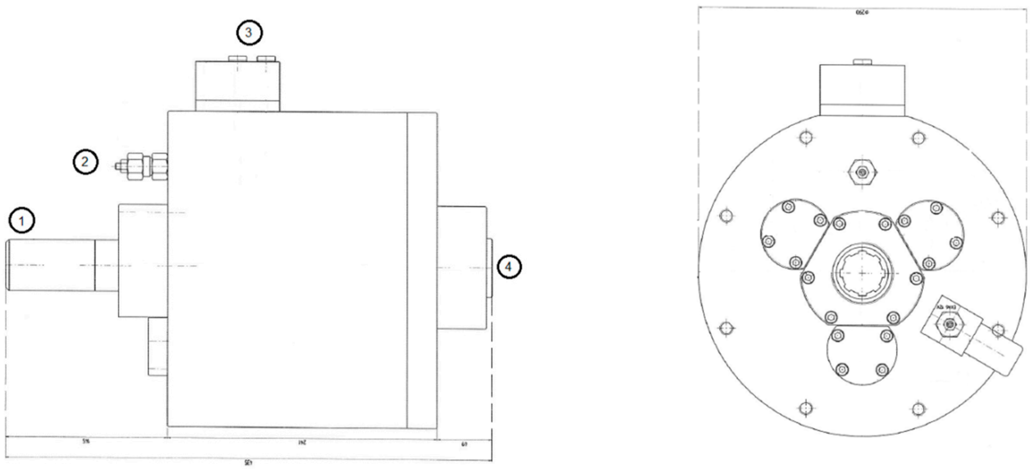

(**a**) (**b**)

Figure 1. Device scheme: (**a**) Lateral view; (**b**) Frontal view. 1. PTO cardan shaft attachment; 2. main valve; 3. electric control; 4. connection to the wagon.

Wheel motion detection is achieved by means of the magnetic proximity sensor that detects the passage of the metal surface of the nuts, mounted on the wheel drum (Figure 2), which, passing through a distance of 1 to 2 mm, make that sensor generates the electrical pulse that is detected by the microprocessor (Figure 3). Five dice are mounted on the wheel to detect even low rotation speeds.

Figure 2. Sensor mounted on the wheel.

Figure 3. Microprocessor and beeper.

When the sensor no longer detects the metal surface on the drum for a time less than or equal to 6 seconds, the system activates the blinking and deactivates the output to release the movement of

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the mechanical organs by stopping its movement in function of the Motion detection by the sensor mounted on the tractor PTO (Figure 4); Consequently, the microprocessor determines the disengagement of the multidisc clutch as a result of the internal pressure loss of the decoupler generated by the electric pump and thus allows decoupling transmission to the manure spreader that stops while the tractor PTO continues to be active.

Figure 4. Sensor on PTO.

In order to prevent the motion transmission in case of failure of connecting to the 12 V power supply, the used clutch is of the "normally open" type.

In this way, the manure spreading organs, located behind the chassis on which the decoupling device is mounted, are no longer connected to the power take off and rotate to neutral until they are stopped in a short time.

A series of field trials showed an average time of stop of the rotors equal to 12 seconds (Table 3). A video showing the operation of the device is available at the link: *https://youtu.be/w5vDZhzcvZY*.

Table 3. Stop time recorded during test.

Test nr.	Stop time (s)
1	13
2	12
3	11
4	12
5	12

As soon as the manure spreader connected to the tractor run again, the sensors, specifically the ones on the wheel's drum, resume signaling, thus resulting in the rearm of the multidisc clutch and then the working bodies resume the motion.

As said before, the system is also equipped with a hold-to-run control which allows to engage or disengage the clutch when the operator has the need to intervene at a standstill. The command must be positioned at a safe distance from the working organs and in the position which allows good visibility of the danger zones.

the technical characteristics of the prototype device installed on the wagon used for the tests are given in Table 4.

Table 4. Technical characteristics.

Microprocessor
SW configuration:
- Alarm sound in case of moving organs in the absence of advancement of wagon

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- Block of the moving parts in the event of stoppage of the wagon
HW Configuration: - 1 standard output for the light or sound signal - 1 standard output for unlocking the movement of the mechanical parts - 1 digital input with 1 to 100 Hz bandwidth and 0/12 V amplitude for the running - 1 digital input with 1 to 100 Hz bandwidth and 0/12 V amplitude for active PTO sensor
Operating conditions: - Power supply: 10/18 V DC with reverse polarity protection and overvoltage impulse - Absorption: 5 mA (excluding signalling devices) - Temperature: from -20°C to +60°C - Maximum humidity: 90% non-condensing - Protection: IP-65
Proximity sensors
XS612 Sensor: - Section: 53 mm - Rated detection distance: 0.16 (4 mm) - Discrete output function: 1 NO - Output circuit type: AC/DC - Rated voltage: 24 to 240 V AC/DC (50/60 Hz) - Switching capacity current: 5 to 200 mA AC/DC - Power supply limits: 20 to 264 V AC/DC - Residual current ≤ 0.8 mA, open condition - Switching frequency: ≤ 1000 Hz DC; ≤ 25 Hz AC - Voltage drop: ≤ 5.5 V, closed condition
XS618 Sensor: - Section: 62 mm - Rated detection distance: 0.31 (8 mm) - Discrete output function: 1 NO - Output circuit type: AC/DC - Rated voltage: 24 to 240 V AC/DC (50/60 Hz) - Switching capacity current: 5 to 200 mA DC - 5 to 300 mA AC - Power supply limits: 20 to 264 V AC/DC - Residual current: ≤ 0.8 mA, open condition - Switching frequency: ≤ 1000 Hz DC; ≤ 25 Hz AC - Voltage drop: ≤ 5.5 V, closed condition

3.1. Applicability

The prototype decoupler has the possibility to be applied to various models of manure spreader: the only technical trick that needs to be adopted is to change the internal solenoid valve pressure. The tested prototype, built according to the power absorbed by the machine (60 kW), had an operating pressure of 15 bar.

Depending on the absorbed power, the pressure must be adjusted according to the following values:

- absorbed power 60 kW → operating pressure 15 bar;

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- absorbed power 74 kW → operating pressure 20 bar;
- absorbed power 88 kW → operating pressure 30 bar.

4. Discussion

The tested mechatronic system would be the most effective and safe as far as the safety of the operator working inside the hopper of the wagon. In fact, the basic concept of "firm wheels - static working organs" would prevent, or would definitely decrease, any type of risk of contact with moving organs.

Nevertheless, as mentioned above, the implementation issues are many. It should also take into account the considerable additional cost that this device would entail for the manufacturers of such machines, which would in some cases raise the sales prices (and hence the purchasing cost for consumers) with a possible drop in sales.

In addition, given the complexity of designing and implementing the system, it is likely that there will be a wide dissent from manufacturers, which would probably be opposed to the proposal for adapting the technical standard relating to the safety of manure spreader wagons.

This technical solution, however, gives the opportunity, depending on the dimensional types of wagons and therefore of the decoupling system, to adapt and put in safety the machinery fleet present throughout the European territory.

To date, the field-tested decoupler is the best solution to overcome the major problems that arise when using the manure spreader wagon: the working time of only 12 seconds from the wheel stop (however adjustable through the programming of the PLC) is sufficient to ensure that it is impossible to enter the hopper when the work organs are still in motion.

In this way, specific activities of the workers that previously were made in absence of safety conditions (and in a way that does not comply with current health and safety regulations) could be carried out in complete safety.

Supplementary Materials: The following are available online at https://youtu.be/w5vDZhzcvZY, Video S1: Promosic: improving the safety of manure spreaders.

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