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Theoretical and experimental analysis of the soil pressure and wear distribution on plough

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"In Africa esiste un concetto noto come Ubuntu, il senso profondo dell'essere umani solo attraverso l'umanità degli altri; se concluderemo qualcosa al mondo sarà grazie al lavoro e alla realizzazione degli altri"

(Nelson Mandela, novembre 2008)

Abstract

Soil engaging tools are subjected to durability problems due to particularly severe wear. During ploughing work wear is generated by the interaction between tillage tool and soil. There are several wear modes on tillage tools, but the predominant cause of material loss is due to the abrasive action of soil particles. Wear rate is strongly affected by soil-tool pressure distribution and it compromises plough performances during its life cycle. The aim of this PhD thesis is the development of a test methodology able to measure and evaluate the pressure distribution on a working plough body using tactile sensors. Field tests were performed with a 4 furrows reversible plough by Gruppo Nardi attached to a New Holland T7.260 tractor and tested at different soils, speeds and ploughing depths. Tractor speed and the horizontal force at the hitch points of the plough were measured. The pressure mean value is influenced both by speed and depth, but each part of the plough has its own characteristic behaviour. The pressure signals demonstrated to be spiky, in fact the pressure mean value was lower than 1% of the maximum value for up to 92% of the ploughed distance. Moreover, spike patterns are markedly affected by the speed especially in terms of the number of spikes and their distribution. The methodology and the results introduced in this PhD thesis will be useful for the validation of mathematical models to simulate the ploughing process, reducing the time required for the engineering design process of optimized ploughs. A possible future development of this research activity is the design of accelerated tests in order to permit a fast validation of plough bodies.

Summary

Figures Summary

Introduction

Experimental Evaluation of the Soil Pressure Distribution on Plough Parts

Influence of the speed on soil-pressure over a plough

Appendix A

Appendix B

Tables Summary

INTRODUCTION

The definition of durability in the field of agricultural machinery is the capability of an apparatus to maintain its functionality during the intended service life without requiring an inordinate degree of maintenance. The development of agricultural machines with high durability is one of the manufacturers main purpose. In fact, the achievement of this goal leads to customer satisfaction due to lower machine inactivity and call-backs (Perozzi et al., 2016). For this reason, the evaluation of durability in agricultural machines through the analysis of load data became of fundamental importance in the last years (Mattetti et al., 2015).

Regarding tillage machines, soil engaging tools are the components more subjected to durability problems (Severnev, 1984; Stawicki et al., 2017). The aim of these tools is the preparation of the soil by mechanical agitation of various types so that crop growth is possible. Among all the tillage tools, plough is still one of the most important and popular primary cultivation tool, despite its invention was thousands of years ago (Mazoyer and Roudart, 2006). The primary objective of ploughing is to cut, crumble and turn the upper layer of the soil, bringing fresh nutrients to the surface while burying crop residue and weeds. Due to the high draught developed, ploughing is a high energy demanding operation, for this reason many studies have been carried out to improve the efficiency of ploughs by optimizing theirs body shape.

One method to obtain optimized plough geometry is through experimental test conducted with different ploughing setups and on different soil types (Godwin, 2007). A more recent approach to this issue is the development of numerical models, which consider soil and operating conditions for a given power availability (Godwin et al., 2007; Shrestha et al., 2001).

However, it is not simple to improve durability and efficiency of plough bodies, even though optimized, because those are subjected to particularly severe wear. Especially the plough body edges are extremely subjected to wear phenomena due to the fact that those are the most active regions during the tillage process. Regarding this aspect, Figure I. 1 and Figure I. 2 show the comparison between a worn ploughshare and its original shape.

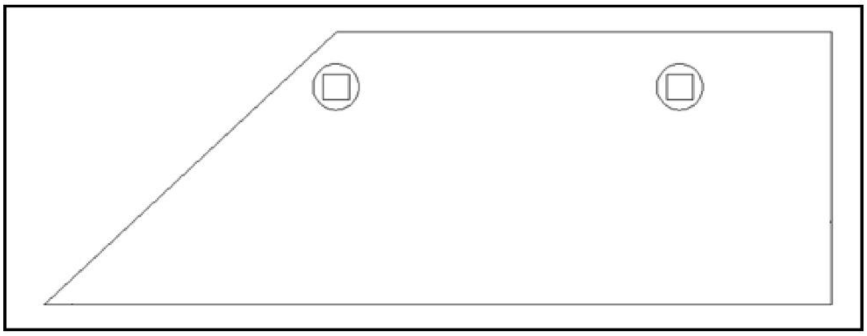

Figure I. 1 Original ploughshare shape

Figure I. 2 Example of a worn ploughshare

Wear has to be minimised because it impairs the designed tool performances, therefore it influences tractor fuel consumption, tillage quality, and maintenance costs due to more frequent part replacements (Horvat et al., 2008). The cause of wear phenomena on tillage tools is mainly due to the interaction between soil and the tillage body. There are several wear modes on tillage tools, such as fretting, chemical action, by impact, but the predominant cause of material loss is by means of the abrasive action of soil particles (Bayhan, 2006). The definition of abrasion wear is the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface (ASTM, 1987) and occurs when a hard rough surface exerts a smoothing action on a softer surface (Straffelini, 2015). One simple equation (eq.1) that correlate the volume wear of cutting edges was developed by Richardson (Richardson, 1969)

$$V = K\,F\,S \;(eq.1)$$

where V is the volume wear, K is a constant that varies for different materials and abrasives, F is the load on the wearing surface and S is the sliding distance. Soil texture is an important factor that influence wear, in fact wear rates are much higher in stony soils. Other important soil parameters that influence the wear rate are the cohesive strength (c) and the volume fraction in the soil (p_v). So, Richardson developed a second equation (eq.2) that correlates the volume wear per unit sliding distance to c and the sum of the products of stone diameter d and p_v.

$$V \propto c \sum p_v\, d \;(eq.2)$$

Eq. 2 gives reliable results especially for clay and silty soils, while in sandy soils the obtained wear rate is overestimated. Even the soil water content is an important parameter that influence the wear rate (Natsis et al., 1999) (Figure I. 3)

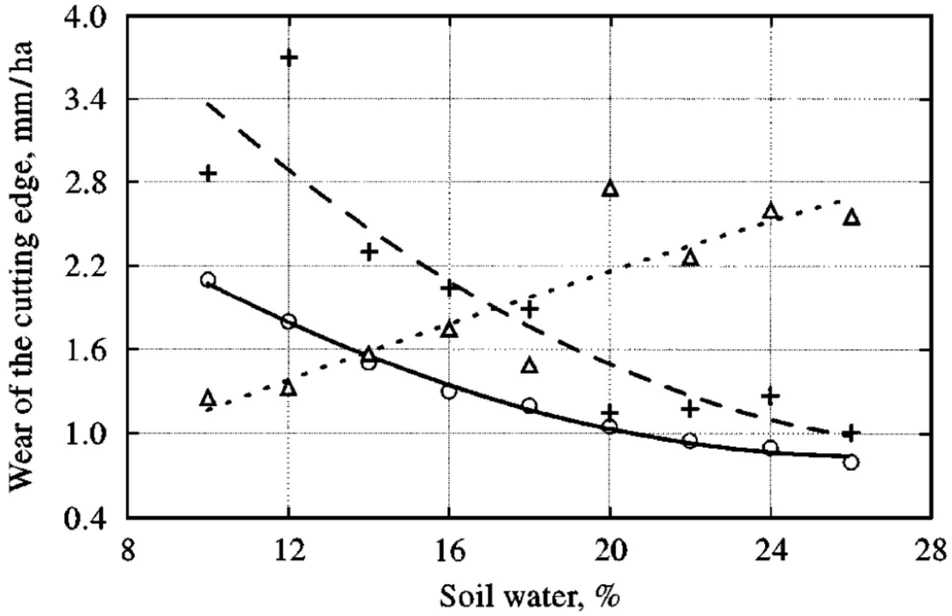

Figure I. 3 The influence of soil water on the wear of the cutting edge of a share. …▲…, sandy soil; --+--, loam soil; —○—, clay soil (Natsis, Papadakis, & Pitsilis, 1999)

With the increase of the soil water content, wear rate decreases for loam and clay soils. On the other hand, wear increase with the increasing of the soil water content in sandy soils. Soil particle angularity influence wear rate, but its effect is strongly related to the soil water content (Gharahbagh Ehsan Alavi et al., 2013)

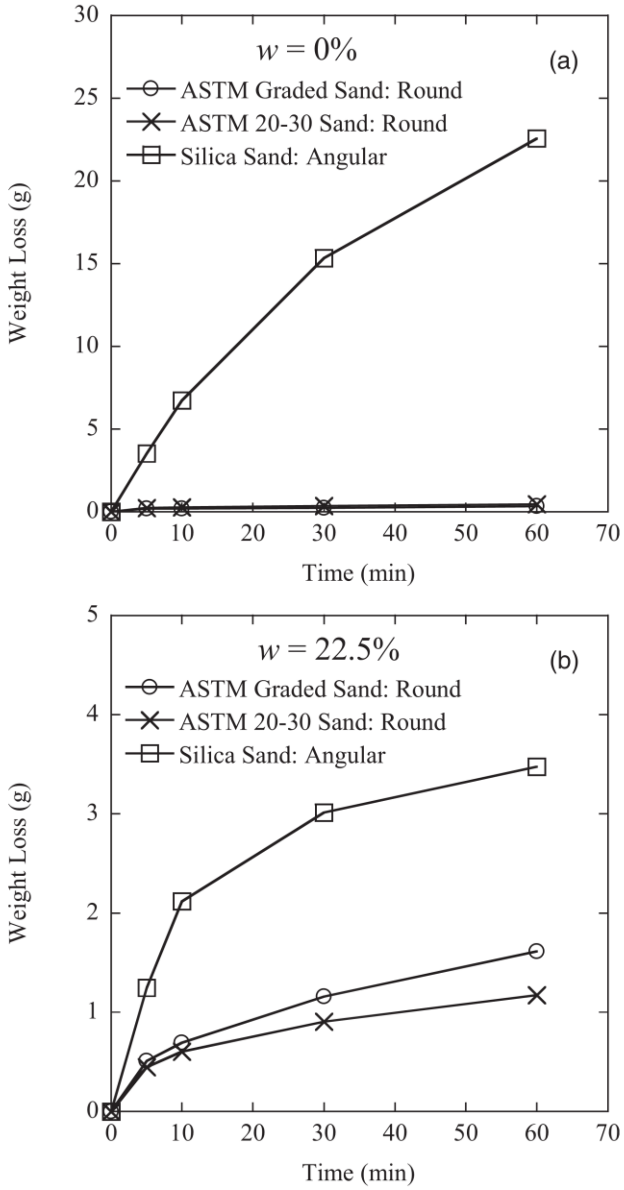

Figure I. 4 Weight loss of the testing device covers with same hardness ratio (tool/mineral) with time in ASTM-graded sand, ASTM 20-30 sand, and silica sand: (a) water content 5 0%; (b) water content 5 22:5% (Gharahbagh Ehsan Alavi, Qiu Tong, & Rostami Jamal, 2013)

The example reported in Figure I. 4 shows that in dry condition, the silica sand (angular particles) produces substantially higher wear rate than the other two sand types (round particles). In the wet soil configuration, one can note that wear rate drops considerably for the silica sand.

Another important aspect that affect wear rate is the relative hardness of the tool material with respect to that of soil particles (Swanson, 1993). In particular, significant reductions in wear rate occur only when the hardness of the wearing material exceeds about 80% of the of the hardest particles of the soil (Richardson, 1967). Tool surface hardening could be done mainly by heat treatment or superficial coating of the tillage material. There are many heat treatments available, but those have in common the basic process in which a metal is heated to a certain temperature and then cooled in a particular manner to alter its internal structure to increase physical and mechanical properties (Wang et al., 2017). Regarding superficial coating, many studies have been carried out to increase the material hardness on tillage tools, such as hardfacing (Bayhan, 2006), powder boriding (Er and Par, 2006) and edge tipping with alumina ceramic (Foley et al., 1984).

However, the research activity of this PhD thesis was more focused on another important factor that influence wear rate in tillage tools: soil-tool pressure distribution in relationship with tool operating conditions. Regarding the latter, few studies were carried out because it can be hardly modelled or measured. One possible method to predict the pressure distribution over the entire tool surface is through accurate mathematical model. The traditional approach to this topic is conducted by means of analytical models based on the earth pressure theories. First, in order to perform an analysis of soil-structure interaction, active and passive earth pressures must be distinguished. While the active pressure is the condition in which the earth exerts a force on a structure, passive pressure is the condition in which a structure exerts a force on the soil. Earth pressures are not the same for active and passive conditions, in fact soil has greater passive resistance. In case of soil-tool interaction, the most basic theories for the evaluation of passive earth pressures were developed by Coulomb and Rankine in the XVIII and IXX centuries. Coulomb's equation (eq.3) represent the shear strength of a material versus the applied normal stress.

$$\tau = c + \sigma_n \tan\varphi \quad (eq. 3)$$

In the previous equation τ and σ_n are respectively the shear and normal stress on the failure plane, c is the soil cohesion, while φ is the angle of internal friction. Both theories are based on strong assumptions on the soil characteristics, specifically it must be isotropic, cohesionless and well drained. Since these conditions are not fulfilled in most of the real case studies, the earth pressure values calculated with these basic theories are unrealistic. For this reason, following analytical models were developed starting from these basic theories but those considered more variables in order to have an increased level of accuracy (McKyes, 1985). From visual observations of soil tillage processes, soil cutting process could be subdivided in three different steps (Ibarra et al., 2005):

1. The compressive force P applied by the tillage blade to a semi-infinite soil medium with an angle δ from the horizontal plane (Figure I. 5) causes the development of compressive stresses in a radial manner (σ_r) . Moreover, vertical compressive stresses (σ_{zz}) are developed by the soil weight, so those increase with depth.

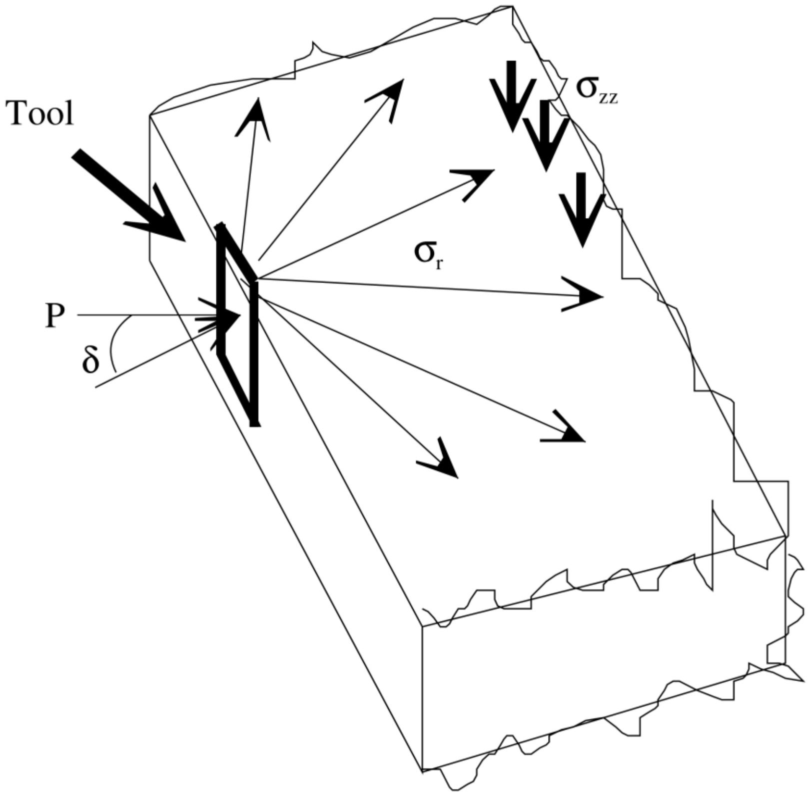

Figure I. 5 Force applied to a semi-infinite medium (Ibarra et al., 2005)

2. Consequently, when the shear strength of the soil is reached, the shear failure plane starts at the bottom of the tool (Figure I. 6). According to the Rankine passive theory, the soil fails in shear in a log spiral shape from the edge of the tool and approximately semi-circular plan shape from the edge of the tool. The sheared segment becomes a finite mass, on which are acting the external stresses from the blade and the rest of the soil.

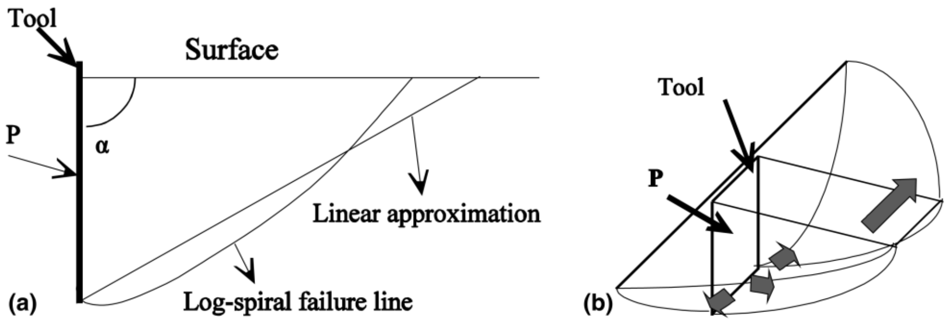

Figure I. 6 (a) Side view of the shear failed soil segment. α is the rake angle with the horizontal plane. (b) Oblique view of shear failed soil segment. (Ibarra et al., 2005)

3. Reaction stresses are produced around the border of the soil segment due to the continuous action of the forces. The development of tensile stresses within the soil segment causes the breaking of soil in a radial manner from the centre of the cross-section (Figure I. 7).

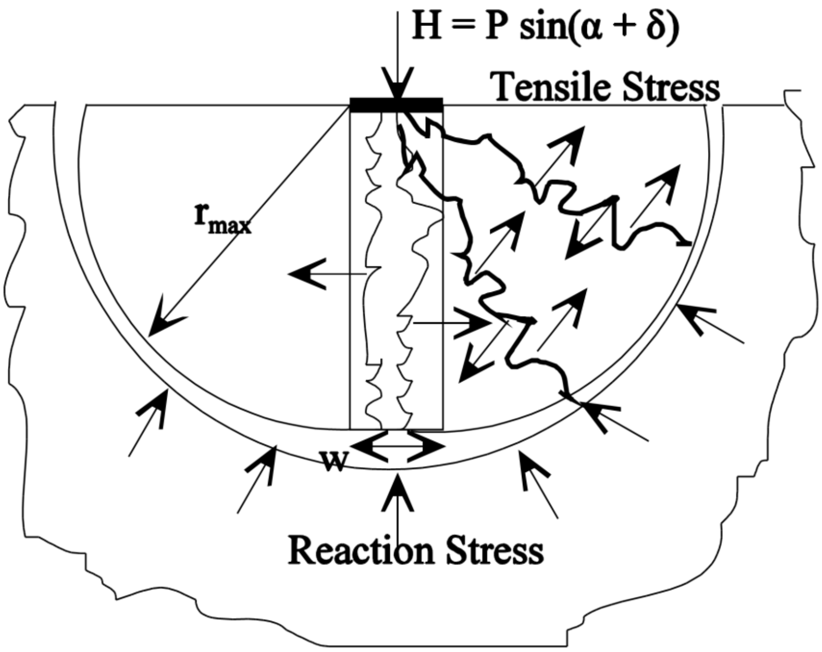

Figure I. 7 Tension failure. The initial shape of the sheared soil volume has one free straight edge perpendicular to the line of action of the draft force, H (Ibarra et al., 2005)

Most of the results obtained from the analytical and numerical models developed in the XX century to investigate the soil-tool interaction were reliable only for very low speed operations (Hettiaratchi and Reece, 1967; Payne, P.C.J., 1956; Reece, 1964). In fact, the parameters used in these models have been studied in a quasi-static condition considering the equilibrium of the soil-tool system. Recently, the increase of computer computational power permitted the development of numerical models that take into account velocity and acceleration of the tool during the soil-tool interaction. The Finite Element Method (FEM) is a numerical method that subdivides a large problem into smaller, simpler parts that are called finite elements. Usually this method is used for structural analysis, however some studies adopted this approach to model the soil–tool interaction (Abo-Elnor et al., 2004; Bentaher et al., 2013; Mouazen and Neményi, 1999). Since this method is based on solid mechanics approach, predictions of these analyses have not been able to address tillage dynamics with high shear rates. One numerical method that improve the understanding of the soil-tool interface mechanism is Computational Fluid Dynamics (CFD) (Karmakar, 2005; Karmakar and Kushwaha, 2006). This method correlates soil rheological behaviour with its dynamic characteristics from fluid flow perspective. A further improvement of the CFD models are the Discrete Element Methods (DEM), where the soil flow is subdivided into a large number of small particles. Today DEM is widely accepted as an effective method of addressing engineering problems in granular and discontinuous materials, especially in granular flows. DEM models became possible for the analysis of soil mechanics only in recent years with the advances in computing power, in fact they requires a huge computational power due to the high number of soil particles that have to be considered (Shmulevich, 2010; Shmulevich et al., 2007; Ucgul et al., 2014).

The results obtained from these mathematical models show that pressure signal on a tillage tool is not constant (D. L. Elijah and J. A. Weber, 1971) with higher pressure spot at the tool edge and in fact, it is the most exposed part to wear (Chi and Kushwaha, 1989). Moreover, pressure increases with the soil shear strength and it is quadratically correlated with tool working speed (Mayauskas, 1959).

Results obtained with mathematical models are crucial for the development of optimised tools, however models have to be validated with extensive experimental studies. Many experimental studies were conducted with the usage of strain gauges applied directly on the tillage tool (Niyamapa and Salokhe, 2000), but this solution is hardly implementable on plough. In fact, the calibration turns out to be complicated because it has to be performed directly on the tool and precision problems could arise due to the curved geometry of ploughs. A solution to this issue is the pressure measurement through several tactile sensors, because they can be calibrated before the installation on the plough surface. This solution was already successfully implemented on other tillage tools like rippers (Chen and Chen, 2008), but problems about the adhesion of the sensors on the plough surface could arise. In fact, the high abrasion action of the soil on the tool requires the implementation of a reliable protection system for all the tactile sensors. Furthermore, this protection system has to be strong enough to assure the necessary protection from the soil abrasion action and simultaneously it has to guarantee that the sensibility of the sensors is not modified.

The aim of this research activity is the development of a test methodology able to measure and evaluate the pressure distribution on a working plough body using tactile sensors. The position of the tactile sensors on the plough body was studied in order to measure the pressure distribution in the most stressed areas. So, 3 tactile sensors were positioned on the ploughshare, 5 on the mouldboard and 2 on the wear plate. As mentioned earlier, a correct design of the tactile sensors protection system is fundamental to have reliable data. In Appendix A of this PhD thesis are reported the different protection systems that were tested during three years of PhD activity. In particular, an in-depth analysis is made for the final version of protection system with whom the data presented in this thesis were acquired. Moreover, in order to have a full comprehension of the tactile sensors behaviour under different load conditions, calibration tests were performed and reported in Appendix B. The materials and methods adopted to conduct the analysis of the pressure on the plough body and the obtained results are presented in two scientific papers included in this PhD thesis. In particular, the paper “Experimental Evaluation of the Soil Pressure Distribution on Plough Parts” is a preliminary analysis on the relationship between soil pressure distribution over a plough, working speed and working depth. The second attached paper “Influence of the speed on soil-pressure over a plough” is a detailed evaluation of the influence of the speed on the soil-plough pressure, focusing the study especially on the analysis of pressure spikes. The position of the sensors in these two papers was the same, the different sensor nomenclature is due to publication reasons imposed by the editors of the two journals.

247

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Experimental Evaluation of the Soil Pressure Distribution on Plough Parts

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Ploughing is one of the most popular and energy-consuming process among conventional tillage treatments. Ploughing tool is worn down during the interaction with soil. This effect increases the tractor fuel consumption, tillage quality, and maintenance costs due to higher replacement rate of tool parts. In this paper a methodology for the measurement of the pressure distribution generated by the soil on plough components is introduced. Field tests were carried out with a four-furrow plough at different speeds and ploughing depths. Pressure on the different parts of the working body was measured with tactile sensors protected through a suitable PVC layer. The analysis of the results shows that the higher mean pressure values are located on the mouldboard and on the wear plate. Moreover, the vehicle speed affects the mean pressure values and in particular, each part of the plough has a different behaviour. The evaluation of the pressure produced by the soil on ploughs is useful for improving the comprehension of the soil cutting process and consequently to design ploughs with higher wear resistance.

1. Introduction

Ploughing is the most important primary cultivation process used for centuries. Its operation is to cut, shear, crumble, and invert the soil in order to obtain the right conditions for crop growth. But ploughing is also an energy demanding activity and for this reason, many studies have been carried out to improve the efficiency of ploughs by optimizing the geometry with the aim of reducing the required specific draft (Shrestha, Singh, & Gebresenbet, 2001). The optimization was carried out by means of experimental tests and numerical models. Anyway, plough bodies, even though optimized, are subjected to particularly severe wear which lead to a reduced tillage quality, to an increased tractor fuel consumption and maintenance costs due to more frequent part replacements. Indeed, a previous study carried out in Australia demonstrated that tillage wear causes an annual cost of 20 million dollars to Australian farmers for the replacement of ground engaging components (Fielke et al., 1993). Over the last decade many studies were carried out in order to study the most severe conditions for the soil engaging tools in terms of wear and on the materials with higher wear resistance (Er & Par, 2006, Jankauskas, Katinas, Skirkus, & Alekneviciene, 2014). Tillage tool wear is affected by soil texture, soil water content, hardness of the tool material, soil particle shapes, tool operating conditions and soil-tool pressure (Natsis, Papadakis, & Pitsilis, 1999). Soil-tool pressure distribution is a little investigated because it can be hardly modelled or measured. The few numerical studies predicted the pressure distribution through Finite Element Modelling (Mouazen & Neményi, 1999), Discrete Element Modeling (Shmulevich, Asaf, & Rubinstein, 2007; Shmulevich, 2010; Ucgul, Fielke, & Saunders, 2014), Computer Fluid Dynamics (Karmakar & Kushwaha, 2006) and analytical models based on earth pressure theory (Hettiaratchi & Reece, 1967; McKyes, 1985).. The few experimental studies measured the soil pressure through tactile sensors (Mattetti et al., 2017) and strain gauges (Elijah & Weber, 1971). Tactile sensors are more convenient than strain gauges when different ploughs have to be tested due to the simplicity of their installation. Indeed, strain gauge requires a fine surface preparation before their installation and the calibration has to be also carried out on the tool which can be unprecise. From all the theoretical and experimental studies about pressure distribution over tillage tools, it can be concluded that the soil pressure is irregular, increases with the soil shear strength, it is

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quadratically correlated with the speed. Moreover, the highest-pressure area is at the edge and in fact, the edge is the most exposed part to wear.
The aim of this paper is a further investigation on the pressure distribution of the soil pressure over a plough under real working conditions and the evaluation of the combined influence of the speed and ploughing depth.

2. Materials and methods

The tests were performed with a four-furrows plough designed by Nardi (Table 1) towed by a New Holland T7.260 tractor with full-powershift transmission (Table 2) (Figure 1).

Table 1: Specifications and settings of the plough adopted in the test

Type of plough	Double or reversible mouldboard
Number of furrows	4
Connection to the tractor	Mounted
Maximum power required by the tractor [kW]	176
Weight [kg]	1720
Width of cut [m]	2.00
Distance between bodies [m]	1.05

Table 2: Specifications and settings of the plough adopted in the test

Tractor Model	New Holland T7.260
Max engine power [kW]	194
Max torque @1500 rpm [Nm]	1349
Transmission	Full power shift (18 forward, 6 reverse)
Weight with ballast [kg]	8900

Figure 1: The tractor and the plough used during the tests

The agricultural soil on which the tests took place is classified as a silty-clay-loam soil according to USDA Textural Soil Classification (USDA, 1987). Moreover, the plastic limit (PL) is 23% and the liquid limit (LL) is 70%, therefore the plasticity index (PI) is 46%, consequently the soil was classified as a high plasticity clays (ASTM, 2010). The mean value of the soil moisture content (on dry basis) measured during the tests was 22.0% with a standard deviation of 1.3% (ASTM, 2009). The mean value and standard deviation of soil bulk density over the field were respectively 1790 kgm^{-3} and 210 kgm^{-3}. Pressure was measured through ten tactile sensors FlexiForce A201 and FlexiForce HT201 (Tekscan, Inc., USA) were placed on a plough body where high wear spots occur. Whereas the soil has a strong abrasive behaviour, each sensor was protected with a PVC layer glued to the plough with a bi-component epoxy resin. The sensor sensitivities were not influenced by this protection system, in fact the calibration curves were verified after the installation. Even the sensor cables were protected from the soil abrasive action by passing them to the rear part of the tool through dedicated holes created on the plough body. In order to evaluate the tractor speed, a VBOX GPS receiver with an update rate of 10 Hz (Racelogic, USA) was installed on the tractor. The output signals coming from the tactile sensors and the GPS receiver were acquired with NI 9234 modules (National Instruments, USA) plugged to a NI cDAQ 9178 USB data acquisition system (National Instruments, USA). A dedicated program was developed with LabVIEW (National Instruments, USA) to record the acquired data on a PC. Test were made at two different ploughing depths, especially at 0.30 m and 0.35 m. The draught control of the three-point hitch was disabled to avoid any vertical displacement of the plough, so the target ploughing depth remained constant during the test. For each ploughing depth, different average ploughing speed were tested setting different combination of engaged gear and engine load. The target speed during a test was kept constant as far as possible by regulating the engine load depending on the resistant load changes due to the spatial variability of soil properties. In particular, average speeds of 2.0, 3.5, and 5.8 km/h were tested for the 0.3 m ploughing depth, while average speeds of 1.9 and 3.6 were tested for the 0.35 m ploughing depth. For the 0.35 m depth were tested only two speeds because the draft applied by the plough did not permit to plough any faster. Each testing condition was performed for 100 m and repeated three times. The data acquired with tactile sensors with a sampling frequency of 500 Hz were divided by the sensing area of the transducer in order to calculate the pressure applied by the soil on each sensor. Then the pressure mean value over the 100 m of the field test (merging the data of each replies) was calculated for each testing condition. Then, the comparison between the obtained pressure mean values was made plotting the results in a color-bar type plot and calculating the percentage difference between each other.

3. Results and discussion

In Figures 1-5 are reported the pressure mean values acquired in the chosen testing conditions. First of all, the highest mean pressure values were located on the mouldboard (MBL) and on the wear plate (WP) in all the tested conditions. One can note that the mean pressure values obtained at 0.3 m ploughing depth are influenced by the ploughing average speed. Indeed, the mean pressures measured on the mouldboard at 3.5 km/h are significantly higher than those recorded at 2.0 km/h. In fact, MBL1, MBL2 and MBL3 recorded increments in the mean pressure value of 300%, while MBL4 and MBL5 show increments of about 70%. The mean pressure values on the mouldboard acquired at 5.8 km/h are slightly lower than the values measured at 3.5 km/h, MBL1 MBL2 and MBL3 values have a drop of 7%, while MBL4 and MBL5 have a drop around 20%. The tactile sensors mounted on the wear plate show different behaviors with the increasing of speed. WP1 show an increase of the mean pressure of about 30% at 3.5 km/h compared with the value obtained at 2.0 km/h, while WP2 remains constant. Both sensors show a slight variation of the mean pressure value at 5.8 km/h compared with the one acquired at 3.5 km/h especially a decrease of 10% for WP1 and an increase of 10% for WP2. The mean pressure value variation from 2.0 km/h to 3.5 km/h on the plough share (PS) is remarkably high, all the tactile sensors recorded an increment of about 150%. Moreover, the mean pressure values on the plough share acquired at 5.8 km/h are the 30% higher than those measured at 3.5 km/h.

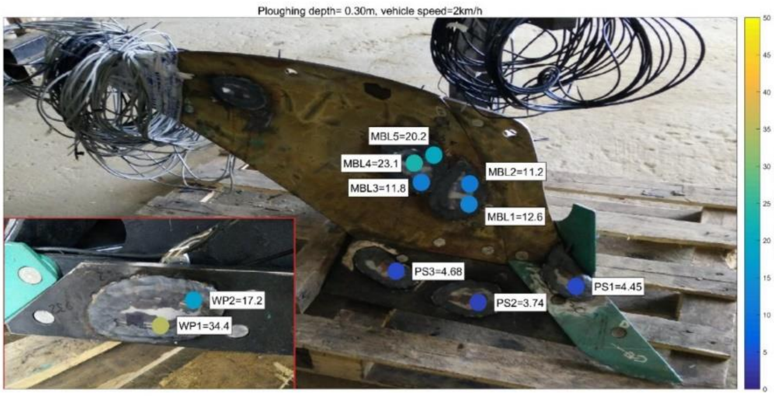

Figure 2: Pressure distribution at 30 cm of ploughing depth and at 2 km/h.

250

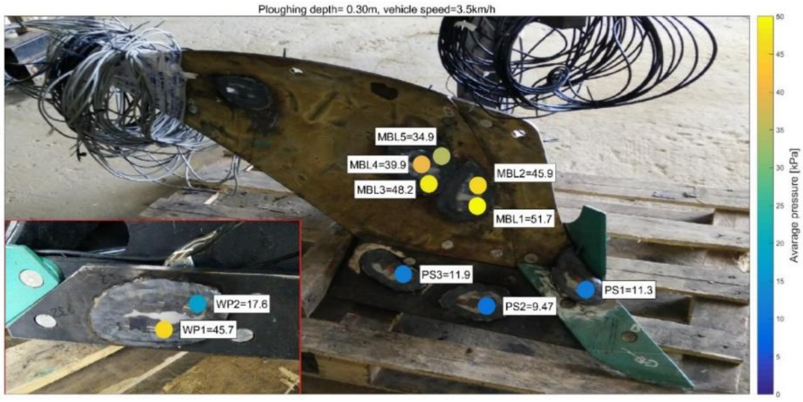

Figure 3: Pressure distribution at 30 cm of ploughing depth and at 3.5 km/h.

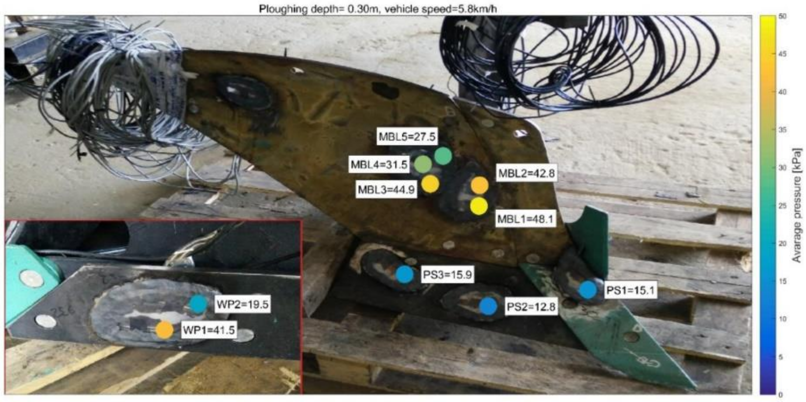

Figure 4: Pressure distribution at 30 cm of ploughing depth and at 5.8 km/h.

The mean pressure values obtained at 0.35 m ploughing depth are influenced by the ploughing average speed only on the mouldboard and on the plough share. The mean pressures measured on MBL1, MBL2 and MBL3 at 3.6 km/h are the 50% higher than those recorded at 1.9 km/h, while the values measured on MBL4 and MBL5 are the 95% higher. The mean pressure value variations from 2.0 km/h to 3.5 km/h on the plough share are similar to those observed for the 0.30 m ploughing depth. In fact, all the tactile sensors recorded an increment of 150%.

Comparing the results obtained with different ploughing depths at almost the same average speed (Figure 3 and Figure 6) one can note that the pressure on the ploughshare doubles with the increase of the depth.

On the other hand, the pressure on the mouldboard significantly decreases with the depth increase, with a drop of the pressures measured by the sensors in the range of 45-71%.

Regarding the wear plate, the sensor WP2 increase with the ploughing depth (+59%), while WP1 remain almost constant.

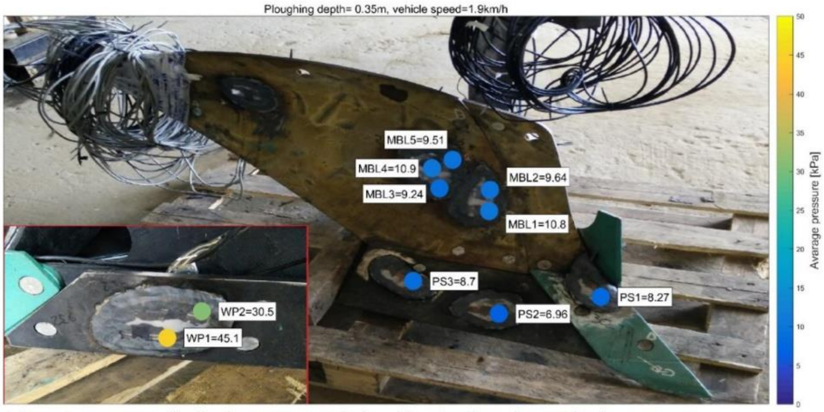

Figure 5: Pressure distribution at 35 cm of ploughing depth and at 1.9 km/h.

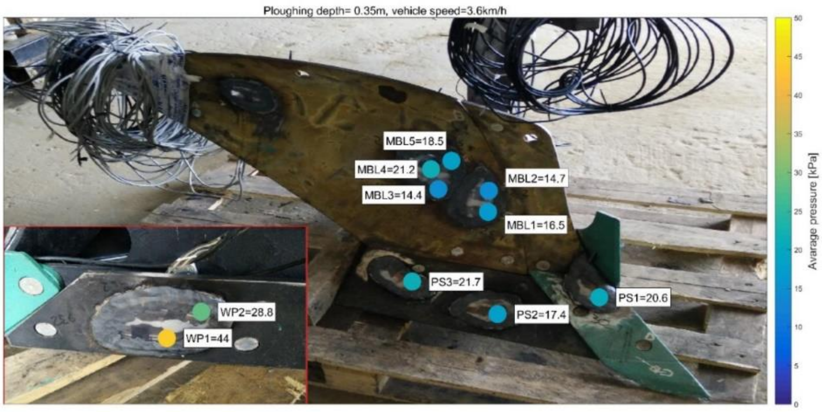

Figure 6: Pressure distribution at 35cm of ploughing depth and at 3.6km/h.

4. Conclusions

In this paper, a test methodology for measuring the soil pressure over a plough was further validated. The data acquired were analysed to evaluate the influence of the combined effect of the speed and ploughing depth on the soil pressure distribution. The analysis of the results shows that the pressure mean values are influenced both by speed and depth, but the effect is different for each part. In fact, the pressures on the mouldboard and on the ploughshare increase significantly with the increment of the average ploughing speed, while the pressure on the wear plate shows a more constant behaviour.

Moreover, maintaining the average ploughing speed constant and increasing the ploughing depth one can note that the pressure on the mouldboard significantly decrease while the pressure on the ploughshare doubles. The methodology and the results introduced in this paper will be useful for the validation of mathematical models able to simulate the ploughing process.

A further development of this work may be the investigation of which soil parameters or conditions affect the pressure/speed relationship and after that the most abrasive conditions for ploughs will be understood.

Thanks to the results of this study, manufacturers will be able to improve the design of their ploughs and farmers will benefit from tools with higher wear resistance.

252

Reference

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BIOSYSTEMS ENGINEERING 156 (2017) 136–147

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Research Paper

Influence of the speed on soil-pressure over a plough

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During ploughing work wear is generated by the interaction between tillage tool and soil. Wear rate on tillage tools is mostly affected by soil-tool pressure distribution and it compromises plough functionality during its life cycle. In this paper, a methodology to measure and analyse pressure signals on a plough has been developed and the influence of the speed was investigated. Field tests were carried out with a four-furrow plough and the pressure on 10 different points was measured with tactile sensors. The plough was tested on a silty-clay-loam soil at three different speeds. The analysis of the results shows that pressure signals are close to zero for a range from 14 up to 92% of the travelled distance and short spikes frequently occur. This behaviour can be explained by the granular structure of soil that determines a non-constant contact between the soil and tool in some points. Spike patterns are markedly affected by the speed especially in terms of the number of spikes and their distribution. Moreover, the mean pressure quadratically varies with the speed in mouldboard (MBL) and ploughshare (PS) while on wear plate (WP) no influence was found because this part is parallel to the ploughing direction. The methodology and the results introduced in this paper will be useful for the validation of mathematical models to simulate the ploughing process but also, to improve the comprehension of the soil cutting process.

1. Introduction

Many methods to analyse load data from agricultural machines have been provided for durability evaluation during the last years (Mattetti, Molari, & Vertua, 2015; Perozzi, Mattetti, Molari, & Sereni, 2016). Durability is the capability of a machine to maintain its functionality during the intended service life. Among all the agricultural machines, plough is the most popular and its function is to cut, crumble and turn the soil in order to create the right conditions for crop growth. Ploughing is a very energy consuming operation because of the developed draught, which varies quadratically with the travel speed and linearly with the tillage depth (Molari,

Abbreviations: DSMV, distance-segmented mean value; DBP, distance base pressure; MBL, mouldboard; PS, ploughshare; TSMV, time-segmented mean value; WP, wear plate.

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Table 1 – Specifications of the tractor used for the test.

Tractor	New Holland T7.260
Max engine power [kW]	194
Max torque [Nm]	1349
Transmission	Full powershift (gears: 18 forward, 6 reverse)
Front tyres	Michelin MACHXBIB 600/65 R28 (12 kPa)
Rear tyres	Michelin MACHXBIB 710/70 R38 (12 kPa)
Mass [kg]	8950

Table 2 – Specifications and settings of the plough adopted in the test.

Type of plough	Double or reversible mouldboard
Number of furrows	4
Connection to the tractor	Mounted
Maximum power required by the tractor [kW]	176
Weight [kg]	1720
Width of cut [m]	2.00
Distance between bodies [m]	1.05

Mattetti, & Walker, 2015; Owende & Ward, 1996). Many studies have been carried out in order to reduce the developed resistance and to increase ploughing efficiency by optimising the shape of plough bodies. This was carried out by means of numerical models (Godwin, O'Dogherty, Saunders, & Balafoutis, 2007; Shrestha, Singh, & Gebresenbet, 2001) and experimental tests (Godwin, 2007). Plough bodies, even though optimised, cannot be easily maintained on service because they are heavily subjected to wear. The most prevalent wear mode on tillage tools is the abrasion but loss of material occurs also by means of impact, fretting, and chemical action (Bayhan, 2006). Wear has to be minimised because it affects tractor fuel consumption, tillage quality, and maintenance costs due to higher replacement rate of tool parts (Horvat, Filipovic, Kosutic, & Emert, 2008). Wear rate is mostly affected by soil texture, water content, particle angularity, hardness of the tool material, and soil-tool pressure distribution (Karmakar & Kushwaha, 2006; Natsis, Papadakis, & Pitsilis, 1999; Swanson, 1993).

Few studies were carried out on pressure distribution between soil and tillage tools, especially by means of analytical models based on the earth pressure theory (Godwin & O'Dogherty, 2007; Godwin & Spoor, 1977; Hettiaratchi & Reece, 1967; McKyes, 1985) and numerical models such as Finite Element Modelling (FEM) (Abo-Elnor, Hamilton, & Boyle, 2004; Bentaher et al., 2013; Mouazen & Neményi, 1999), Discrete Element Modelling (DEM) (Shmulevich, 2010; Shmulevich, Asaf, & Rubinstein, 2007; Ucgul, Fielke, & Saunders, 2014), and Computational Fluid Dynamics (CFD) (Karmakar & Kushwaha, 2006). From these studies, pressure signal on a tillage tool is irregular and the pressure is correlated with soil shear strength (Elijah & Weber, 1971), working depth, and tool travelling speed (Mayauskas, 1958). Moreover, by using FEM, the higher pressure areas were found at the tool edge (Chi & Kushwaha, 1989). Accurate mathematical models are necessary to design optimised tools because they allow the prediction of the pressure distribution over the entire tool surface in many different operating conditions. Mathematical models have to be validated and therefore more extensive experimental studies have to be carried out. In

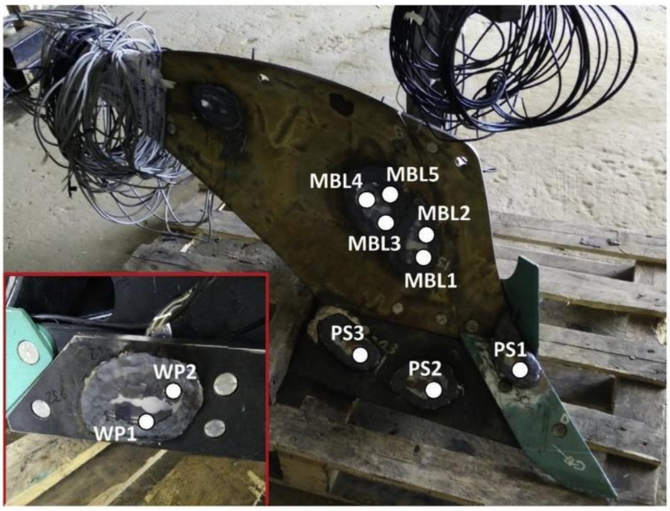

Fig. 1 – Positions of the pressure sensors and denomination of pressure signals.

Fig. 2 – Three-point hitch coupler and load sensing pins used for the test.

most of the previous studies, strain gauges were successfully used (Elijah & Weber, 1971; Mayauskas, 1958; Niyamapa & Salokhe, 2000) but, they require a fine surface preparation before the attachment, the calibration has to be also carried out on the tool and it may not be very precise due to the curved geometry of ploughs. For these reasons, the measure of soil pressure on different tools can be very time consuming. Flexible tactile force sensors were successfully used for measuring the pressure on a subsoiler in order to validate a DEM model (Chen & Chen, 2008). They can be calibrated before the installation on a tool surface, but no detailed analysis of the measured pressure has been provided so far.

The aim of this paper is the measure of the soil-plough pressure under real working conditions using tactile sensors and the evaluation of the influence of the speed on the measured pressure.

2. Materials and methods

The tests were carried out with a New Holland T7.260 (Table 1) fitted with a four-furrows plough designed by Nardi (Table 2).

The plough-soil pressures were measured through ten tactile sensors, especially seven FlexiForce A201 and three FlexiForce HT201 (Tekscan, Inc., USA) placed on a plough body, in locations where large wear rates were observed in a worn plough body (Fig. 1).

Due to the need of protecting sensors from soil abrasive action, sensors had to be placed far from the plough edges. Sensors were protected with a combination of a bi-component epoxy resin and an abrasion resistant PVC layer. Calibration curves were verified after the application of the protection in order to ensure that the protection would not have affected sensor sensitivities. Sensor wires were protected from soil abrasion by passing them through holes in the plough body to the rear of the tool, thus a limited modification of the plough profile was made.

Each sensor was connected to a FlexiForce Quickstart Board (Tekscan, Inc., USA) that converts the sensor output signal into an analogue voltage signal. The horizontal forces at the hitch points of the plough were measured through load sensing pins (N.B.C. Elettronica Group s.r.l., Italy). These sensors have a full-scale range of 98 kN and provide a maximum voltage output of 10 V. In order to keep sensor axis aligned to the longitudinal direction of the tractor, a three-point hitch coupler was used to connect the implement to the three-point hitch to prevent the relative rotation between the pins and the frame (Fig. 2).

The tractor speed was measured with a VBOX GPS receiver with an update rate of 10 Hz (Racelogic, USA). The VBOX GPS system and FlexiForce Quickstart Boards output signals were acquired with NI 9234 modules (National Instruments, USA), while the output signals of the load sensing pins were acquired with a NI 9215 module (National Instruments, USA). All these modules were connected to a NI cDAQ 9178 USB data acquisition system (National Instruments, USA). Sensor data was recorded on a computer through a specific program developed in LabVIEW (National Instruments, USA). The data acquired with tactile sensors was divided by the sensing area of the transducer in order to calculate the pressure applied by the soil to the sensor. The tractor draught was calculated by adding the hitch forces, and the ploughed distance was calculated through numerical integration of the speed signal.

The field tests were performed on a silty-clay-loam soil according to USDA Textural Soil Classification (USDA, 1987). The liquid limit (LL) and the plastic limit (PL) of the soil are respectively 70% and 23%. Consequently, a plasticity index (PI) of 46% permits to classify the soil as a high plasticity clays (ASTM, 2010). The mean value and the standard deviation of soil bulk density over the field were respectively 1790 kg m^{-3} and 210 kg m^{-3}; while the mean value and the standard deviation of the soil moisture content (on dry mass basis) were respectively 22.0% and 1.3% (ASTM, 2009). Soil moisture content, under these conditions, is close to the optimum value for

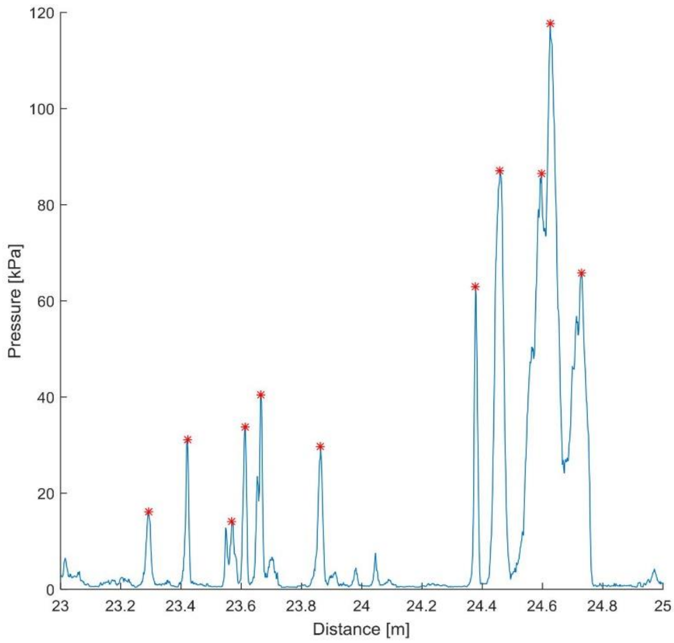

Fig. 3 – Spike detection for the speed of 3.5 km h^{-1}. Pressure signal (—), detected spikes (*).

soil workability (Dedousis & Bartzanas, 2010; Dexter & Bird, 2001).

The tests were carried out at 0.3 m of ploughing depth setting the engine load and the gear in order to maintain the following 3 average speeds of 2.0, 3.5, and 5.7 km h^{-1}. Each testing condition was performed for 100 m. The ploughing depth was kept constant by disabling the draught control of the three-point hitch to avoid the influence of vertical displacement of the plough on the results. On the contrary, the speed was kept constant as much as possible by slightly adapting the engine load to the draught force change due to spatial variability of soil properties.

Speed and draught signals were analysed by calculating the mean value and the difference between the maximum and the minimum values in order to quickly describe each test conditions. Signals were evaluated as stationary through the segmenting method (Yang, 2009). In particular, all signals were framed into segments of 15 s width and the mean value of each segments were calculated, called in the following Time-Segmented Mean Values (TSMV).

For each pressure signal, spikes with a prominence higher than 7 kPa were detected (Fig. 3) and in this way, high frequency signal noise that lead to small pressure oscillations, was removed. The detected peaks were then grouped into pressure intervals of 20 kPa width so, the distributions of the spike peaks were calculated and the influence of the speed on the spike patterns was analysed.

The correlation between pressure and speed was evaluated through a regression analysis. In particular, speed and pressure signals were framed into segments of 33 m width where the mean value (called in the following Distance-Segmented Mean Values, DSMV) was calculated for each segment. In order to estimate the amount of ploughed distance where spikes do not occur, the Distance Base Pressure (DBP), as the total distance when the pressure is lower than 4 kPa, was calculated.

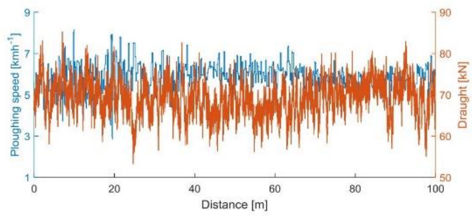

Fig. 4 – Speed (—) and draught (—) with respect to the ploughed distance at the 5.7 km h^{-1}.

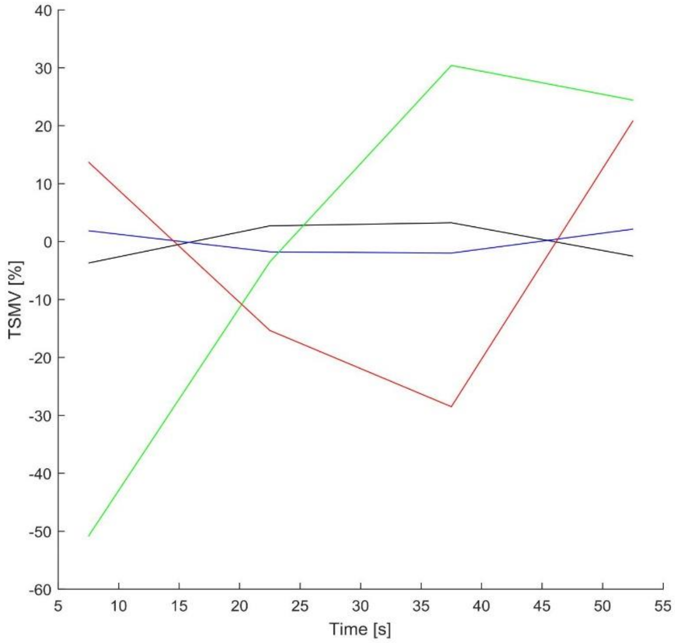

Fig. 5 – TSMVs at the ploughing speed of 5.7 km h^{-1} for: speed (—), draught (—), MBL3 (—) and PS2 (—).

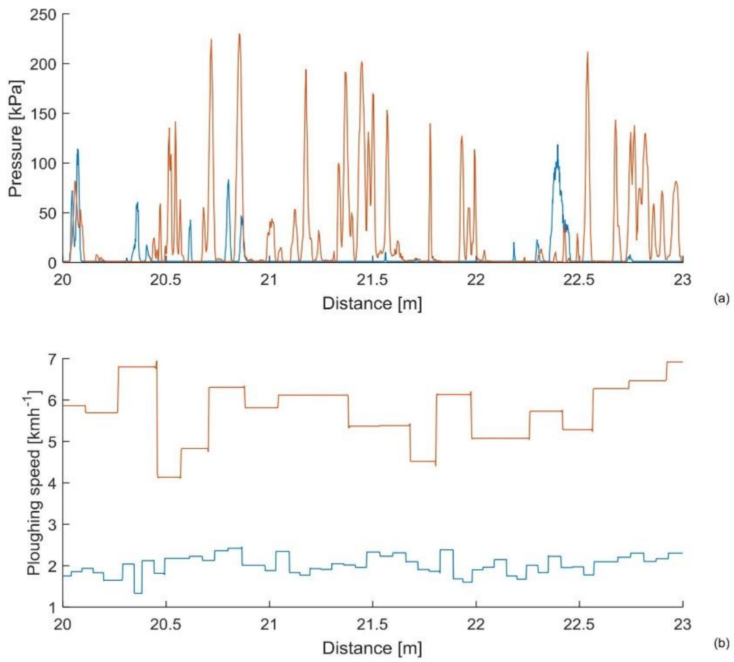

Fig. 6 – Portion of (a) PS2 signals and (b) speed signals at 2.0 (—) and 5.7 km h^{-1} (—).

BIOSYSTEMS ENGINEERING 156 (2017) 136–147

3. Results and discussion

A relevant variation of the draught occurred during the test due to a notable fluctuation of the ploughing speed (Fig. 4). The highest draught variation was obtained at the speed of 5.7 km h^{-1} where the difference between the minimum and the maximum values of the draught was 32 kN instead, the mean value of the draught was 69 kN. The difference between the minimum and the maximum values of the speed was 5.4 km h^{-1}.

A sample of TSMVs for speed, draught, and two pressure signals measured at 5.7 km h^{-1} are reported in Fig. 5. Draught and speed show values lower than 4% and for this reason, the test can be considered stationary. On the other hand, TSMVs of pressure signals show more distributed values and therefore, the soil-tillage interaction cannot be considered a stationary process.

In fact, pressure signals were characterised by a base pressure and large spikes (Fig. 6). The base pressure was less than 4 kPa and independent by sensor position or ploughing speed. The spikes were probably caused by the fact that soil is a granular material with a non-uniform strength that causes a variable reaction with the plough.

The distributions of the spike peaks of all the recorded pressures at the 5.7 km h^{-1} condition are reported in Fig. 7. The number of occurrences of the spike peaks are very different from each other, but a similar trend may be recognised. Indeed, all the distributions sharply decrease with the pressure and no gap can be observed, with the exception of the right tail characterised by isolated points (Fig. 7). Therefore, small peaks dominate the large ones and in fact, the 90th percentile of all the distributions is included between 31% and 54% of the maximum measured pressure.

Signals from pressure sensors placed on the mouldboard (MBL) were more irregular than those recorded from sensors mounted on the other parts probably because the impacting soil in this part was looser. Consequently, a higher number of spikes are observed in these signals at all speeds. The only exception is the pressure MBL3, probably because the sensor was located close to the protection edge which might have affected the soil flow over the sensor. Peaks at lower intervals (between 50 and 150 kPa) of the distribution MBL5 are much more frequent than MBL4 even if the sensors were placed less than 60 mm apart from each other, which means pressure distribution is rather irregular over the MBL. The distributions of WP1 and WP2 are flatter compared to that of the other pressures due to a low number of small peaks and a large number of high peaks with respect to the other parts. The lowest number of

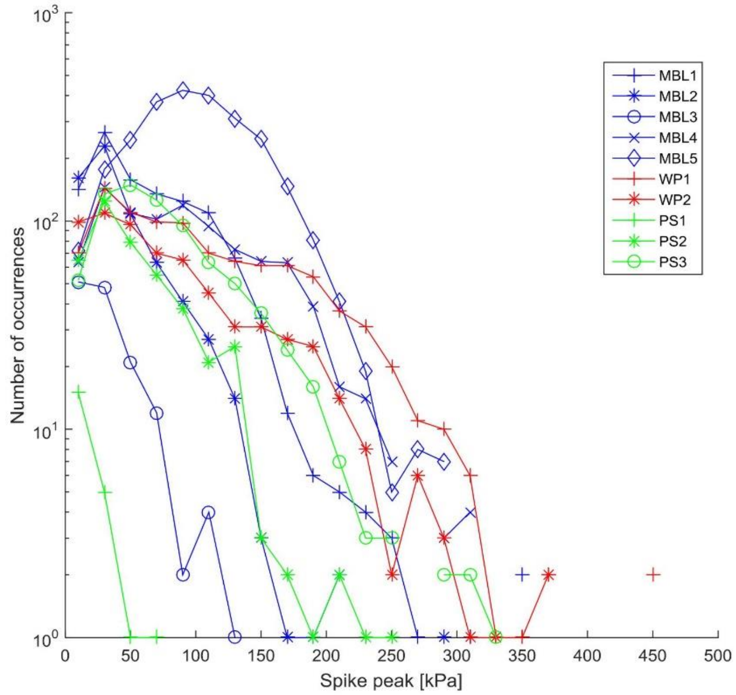

Fig. 7 – Distributions of the spike peaks of all pressure signals at the speed of 5.7 km h^{-1}.

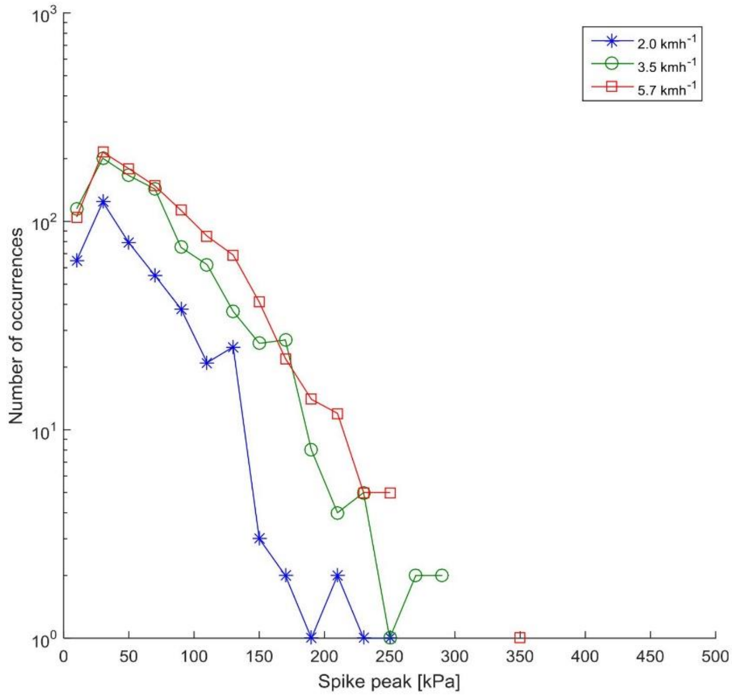

Fig. 8 – Distributions of the spike peaks for PS2 at the testing speeds.

spikes is obtained for PS1 because the sensor was placed too close to the coulter, which probably deviated the soil flow slightly away from it.

The pressure distributions were influenced by the speed but not in the same way. For the ploughshare (PS), the number of occurrences increased with the speed for most of the pressure intervals and consequently the number of detected spikes increased (Fig. 8). As instance for pressure PS2 at 3.5 and 5.7 km h^{-1}, the number of spikes is, respectively, 2.1 and 2.4 times greater than at 2.0 km h^{-1}. The maximum measured pressure at 3.5 and 5.7 km h^{-1} is, respectively, 21% and 41% greater than the maximum measured pressure at 2.0 km h^{-1}. The PS is mainly responsible for soil cutting and the speed affects the cutting process because it controls the rate of soil angular deformation (Gill & Vanden Berg, 1967; McKyes, 1985).

With reference to the MBL, the number of occurrences of the distribution did not increase monotonically with the speed for most of the pressure intervals. For example, the distributions at the testing speeds for pressure MBL4 are reported in Fig. 9 where only at the tails of the distribution, the number of occurrences at 5.7 is greater than at 3.5 km h^{-1}. For this reason, the number of detected spikes at 3.5 is 15% greater than that at 5.7 km h^{-1}. Moreover, the maximum measured pressure at 3.5 and 5.7 km h^{-1} is approximately 38% greater than that at 2.0 km h^{-1}. For the MBL, the effect of the speed is different with respect to the PS, probably because the speed is higher and the produced clods are smaller. Consequently the inertial effect of the clods on the pressure should be less severe (Gill & Vanden Berg, 1967) as demonstrated also by a larger number of spike peaks lower than 100 kPa at 5.7 km h^{-1} compared to that obtained at 3.5 km h^{-1}.

On the contrary, the speed does not affect the distributions of pressures on the wear plate (WP); indeed, the number of occurrences were mostly the same for all the pressure intervals. With reference to the pressure WP2 the number of spikes at 3.5 and 5.7 km h^{-1} is almost the same than at 2.0 km h^{-1} and the maximum pressure is at 3.5 and 5.7 km h^{-1}, respectively, 5% and 1% greater than that at 2.0 km h^{-1} (Fig. 10). The WP is located at the rear part of the plough and is not responsible for the soil cutting and for this reason the pressure is not affected by the speed.

The speed affects not only the distributions of the spike peaks but also the DSMVs of pressure signals. The relationship between pressure and speed for most of the measured pressures is quadratic. Indeed, the residuals are fairly well placed alongside the regression curve as reported in Fig. 11. The trend is coherent with a quadratic relationship between draught and speed (Godwin et al., 2007). Moreover, for MBL4 the

BIOSYSTEMS ENGINEERING 156 (2017) 136–147 143

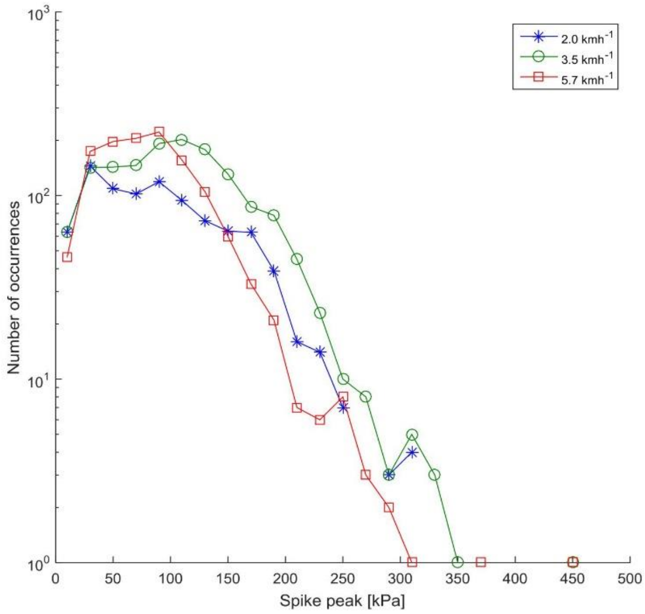

Fig. 9 – Distributions of the spike peaks for MBL4 at the testing speeds.

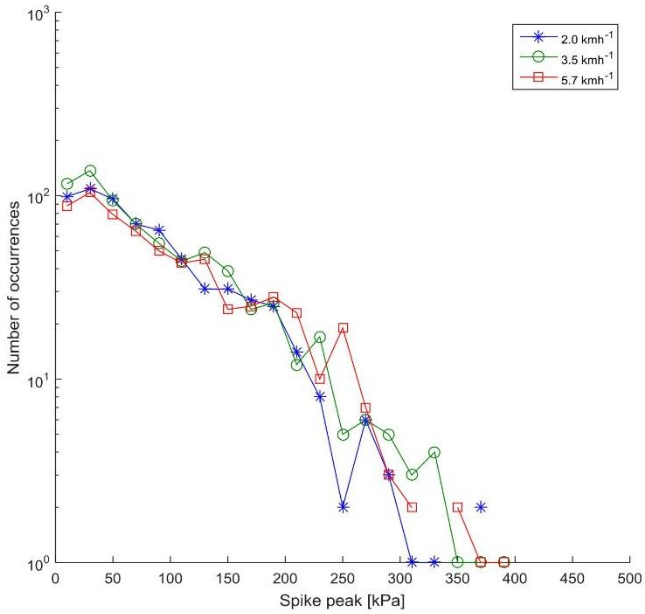

Fig. 10 – Distributions of the spike peaks for WP2 at the testing speeds.

144 BIOSYSTEMS ENGINEERING 156 (2017) 136–147

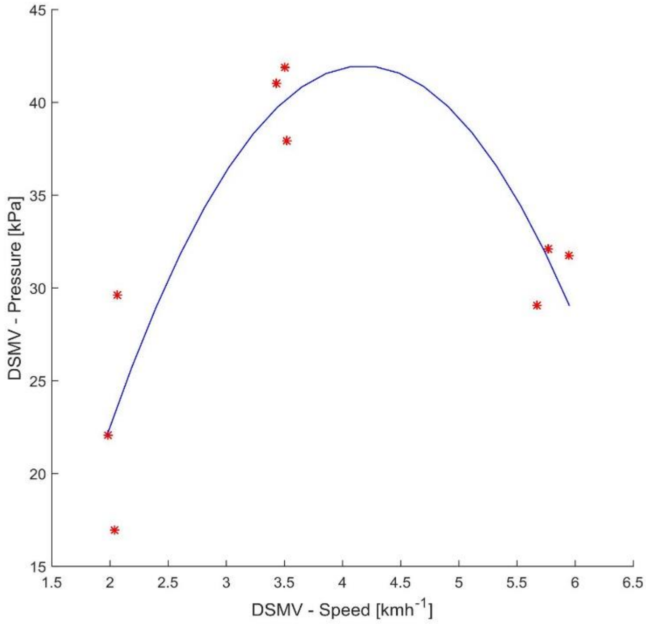

Fig. 11 – Pressure vs speed for MBL4.

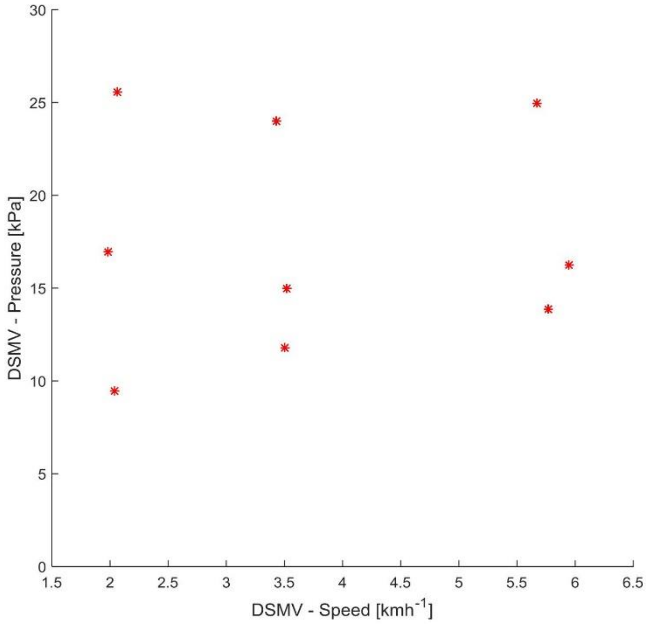

Fig. 12 – Pressure vs speed for WP2.

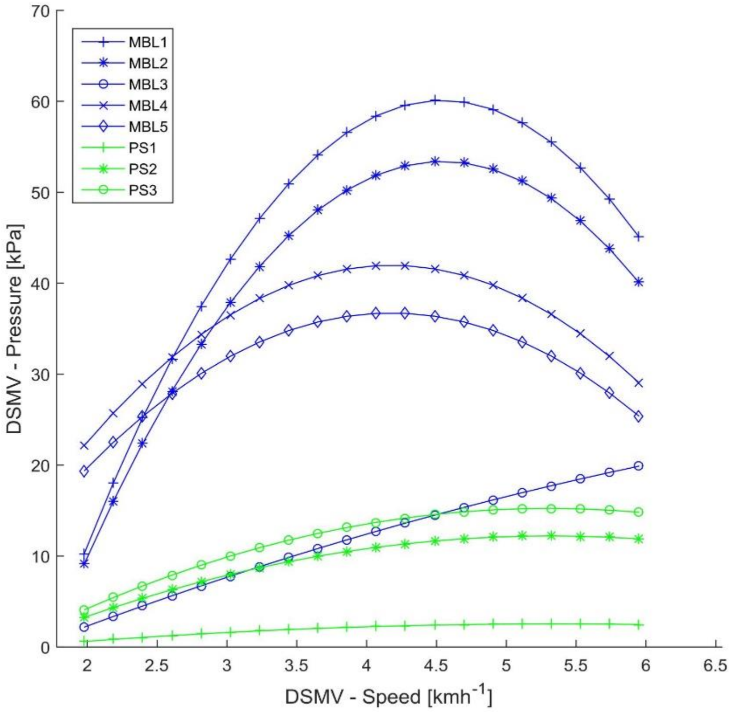

Fig. 13 – Pressure vs speed on mouldboard and ploughshare.

maximum pressure DSMV is lower than 10% of the maximum measured pressure.

The distributions of spike peaks of the pressures on the WP were not affected by the speed, as suggested by the poor correlation obtained between the DSMVs of the speed and the pressures, probably due to the longitudinal orientation of this part with respect to the ploughing direction (Fig. 12).

The regression curves of all pressures on MBL and PS are reported in Fig. 13, data of the WP are not included because they are poorly correlated with the speed. In Table 3, the related R-squared values are reported. The high R-squared values indicate a strong relationship between speed and pressure. Pressure DSMVs on MBL are much higher and more influenced by the speed than that on PS probably due to smaller angles between the normal to the surface of the working bodies and the ploughing direction. The maximum values of all the regression curves of the pressure DSMVs on the MBL, with the exception of MBL3, are located at the speed range from 4.2 to 4.5 km h^{-1} and then the curves decrease. On the other hand, a different trend is obtained on the PS where the pressure increases with the speed up to 5.3 km h^{-1} and then it is almost constant. Moreover, the regression curves of pressures measured on the same part are rather different and therefore a notable pressure gradient exists. In fact, the maximum values of the regression curves for the MBL and PS vary, up to 66% and 27% respectively with reference to the minimum value of their group (pressure MBL3 and WP1 were not included in calculations).

Table 3 – R-squared value of the regression curves.

Pressure	R-squared
MBL1	0.931
MBL2	0.931
MBL3	0.750
MBL4	0.804
MBL5	0.805
WP1	0.094
WP2	0.005
PS1	0.753
PS2	0.889
PS3	0.892

In Fig. 14 the DBP for the all pressure signals with respect to the speed is reported. The same considerations about the effect of the speed on the number of spikes and their amplitude can be also made for the DBP because most of the spikes are isolated rather than grouped (Fig. 3). An interesting result is that DBP can reach very high values especially at 2.0 km h^{-1}

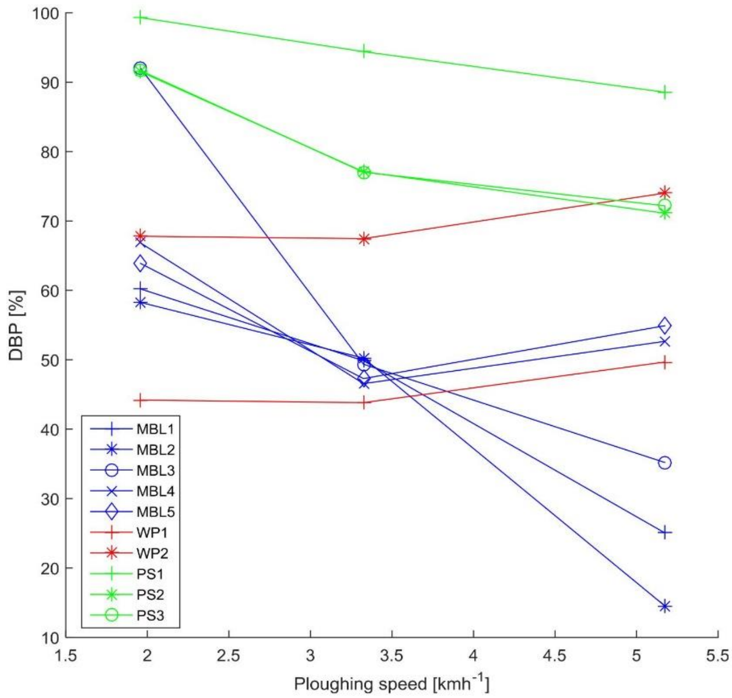

Fig. 14 – Influence of the speed on the DBP.

where it ranged from 44% up to 92%, while at 5.7 km h^{-1}, it ranged from 14% up to 74% (PS1 is not included).

4. Conclusions

A methodology to measure and analyse the soil-pressure over a plough has been introduced by using tactile sensors. The highest pressures were measured in the MBL with a speed of 4.2 km h^{-1} and then decrease with the speed. The obtained pressure on the PS were of the same order of magnitude of that published by others (Mayauskas, 1958) and a similar influence of the speed on the PS pressure was found albeit the speed range was more extreme in this study. Pressure signals are spiky and they can reach very high values but the pressure was lower than 1% of the maximum value for up to 92% of the ploughed distance. Spike patterns were markedly affected by the speed in terms of number of spikes, spikes distributions, and the ploughed distance with a pressure lower than 4 kPa. The effect was the strongest on the MBL, while none was observed on the WP for the different orientation of the surface. Moreover, the mean pressure over a distance was less than the 10% of the maximum measured pressure. For these reasons spikes retained most of the information about the process and this proved the need to introduce a suitable method to analyse soil pressure signals.

The results will be useful for validating numerical models able to reproduce the soil cutting process. These will be useful to optimise plough geometries in order to limit the maximum pressure, increase the degree of soil loosening, and consequently increase the ploughing efficiency. In addition, the results obtained from this study could be adopted in order to properly select wear resistant materials for the components and to design accelerated tests for the evaluation of wear resistance of ploughs under real operating conditions. Due to the fact that pressure was mostly lower than 4 kPa, high acceleration factors can be achieved by reducing the ploughed distance at the base pressure. Therefore, the investigation of which soil parameters or conditions may reduce this distance is necessary and should be interesting as a future work. This will allow a fast validation of plough bodies, which now is mainly based on limited field tests where testing conditions are not carefully controlled. Thanks to the results of this study, manufacturers will be able to improve the design of their ploughs and farmers will benefit from tools with higher wear resistance.

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CONCLUSIONS

One of the fundamental objective of agricultural machineries manufacturer is the design of highly durable machines. The reason why this aspect is highly considered is that it leads to cost saving and increased customer satisfaction due to lower machine inactivity and call-backs. The evaluation of durability has an even more important role in the design of soil engaging tillage machines because those are more subjected to durability problems. This is due to the fact that the preparation of the soil is performed by a mechanical soil-tool interaction. In particular, the plough cut, crumble and turn the upper layer of the soil, developing a high draft force on the tractor. Since ploughing is a high energy demanding operation many numerical models and experimental tests have been carried out to improve the efficiency of ploughs by optimizing theirs body shape. Moreover, efficiency and durability of a plough are strictly correlated because the latter is subjected to particularly severe wear during its operation. So, the original shape of the plough, even though optimized, is modified by wear phenomena during its lifetime. The performances of the tool are strongly altered by wear phenomena, it influences for example tillage quality, maintenance costs and tractor fuel consumption. There are several wear modes on tillage tools, but the predominant cause of material loss is by means of the abrasive action of soil particles. Wear rate on tillage tools is influenced by the soil characteristics, the relative hardness of the tool material with respect to that of soil particles and the soil-tool pressure distribution. Regarding the latter, one possible method to predict the pressure distribution over the entire tool surface is through accurate mathematical model. These mathematical models could be divided in two macro-categories: analytical models based on the earth pressure theory and numerical models. However, even if the obtained results are crucial for the design of optimised tools, models have to be validated with experimental studies. Therefore, the aim of this research activity was the development of a test methodology able to measure and evaluate the pressure distribution on a working plough body using tactile sensors. The first step that has been done to reach this objective was the development of a reliable protection system for all the tactile sensors. After several experimental tests, the designed protection system demonstrated to be strong enough to assure the necessary protection from the soil abrasion action and simultaneously it guarantees that the sensibility of the sensors was not modified. Then, the tactile sensors were calibrated and tested under different load conditions in order to have a deep knowledge of their characteristics. Subsequently, field tests were performed with a Gruppo Nardi 4 furrows reversible plough attached to a New Holland T7.260 tractor at different speeds and ploughing depths. The analysis of the results shows that the pressure order of magnitude measured on the ploughshare and its relationship with the speed agree with the results available in literature (Mayauskas, 1959). Moreover, the results show that the measured pressure mean values are influenced both by speed and depth, but each part of the plough has its own characteristic behaviour. Considering a fixed ploughing depth, the pressures on the ploughshare and on the mouldboard increase significantly as the average ploughing speed increase, while the pressure on the wear plate shows a more constant behaviour. Moreover, considering a fixed ploughing speed, with the increase of the ploughing depth one can note that the pressure on the mouldboard significantly decrease while the pressure on the ploughshare doubles. These different behaviour of the plough parts is mainly due to the different role that those have during the soil cutting process. The pressure demonstrated to be spiky, this behaviour can be explained by the granular structure of soil that determines a non-constant contact between the soil and tool in some points. So, the research activity focus moved on a deeper investigation of the influence of the speed on the soil-plough pressure, especially on the analysis of pressure spikes. Especially on the mouldboard, spike patterns were strongly affected by the speed in terms of number of spikes, spikes distributions, and the ploughed distance with a pressure lower than 4 kPa. The obtained results fulfil the primary objective of this research activity, the measurement of experimental data in order to validate numerical models able to reproduce the soil cutting process. Consequently, the adoption by the agricultural machineries manufacturers of these numerical model will improve the design of their ploughs. In particular, the plough efficiency could be improved optimizing its geometry in order to limit the maximum pressure acting on the working body. An interesting future development which could produce important supplementary results regarding this aspect is the evaluation of plough parts volume change. One possible method to reach this goal is through the usage of a 3D scan, scanning the parts before and after the field tests in order to quantify the material loss due to wear. Then, with an in-depth knowledge of the pressure and wear distributions on the plough body, manufacturers are able to properly select wear resistant materials for the more stressed components in order to increase the durability of theirs ploughs. Regarding this topic, the paper "On the abrasive wear distribution acting on ploughshares by means of a reverse engineering tool" (Filippo Cucinotta, Lorenzo Scappaticci, Michele Mattetti, Felice

Sfravara, Fabrizio Morelli, Francesco Mariani, Massimiliano Varani) has been already submitted to a scientific journal and it is under evaluation. Another future development of this research activity is the replication of this measurement methodology on a wide variety of soil types and conditions. Then, an in-depth analysis could be conducted to find out which soil parameters and conditions are more stressful for the plough body pressure distribution. This would permit the design of accelerated tests in order to permit a fast validation of plough bodies. In fact, since the pressure was mostly very low, high acceleration factors can be achieved by reducing the ploughed distance at the base pressure. However, find a field with the desired homogeneous soil parameters all over its extension is almost impossible. A possible solution to this issue is the creation of a soil tank facility filled with soil that has the desired characteristics. Moreover, in order to have an even more accurate pressure measure, new pressure sensors are going to be installed on the plough (Strain Measurement Devices Ltd, UK). The sensibility performances of these new sensors are better than the tactile sensors used in this research activity, and since those are made in steel, the design of a less invasive protection system is possible.

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APPENDIX A

The high abrasion action of the soil on the tool requires the design of a reliable protection system for the tactile sensors applied on the plough surface. Then, the first important characteristic that this system must have is a high abrasion resistance. This aspect has to be applied not only for the tactile sensors, but also for the cables that connect these to the acquisition system. Contemporarily, the protection system has to guarantee that the sensibility of the sensors is not modified, so proper material must be used.

A.1 Preliminary studies on different adhesive types

The simplest method to install the tactile sensors is to paste those directly on the plough surface without any interface between soil and sensor. In this way the sensibility of sensors is guaranteed, so different types of adhesive were tested in order to investigate if this solution was possible. Since the tactile sensors are made in polyester, the adhesive types that are more efficient for the bonding on metal are epoxy resin and polyurethane adhesives. However, preliminary test showed that the soil abrasion action was too strong, in fact the sensor detached after few meters with both adhesive types (Figure A.1).

Figure A.1 Preliminary test with epoxy resin, condition of the bonding after the test. The sensor detached after few meters of test

Another simple method to fix the sensors to the tool surface is through the use of abrasion resistance duct tape (Chen and Chen, 2008), but the curved geometry of the plough doesn’t allow the implementation of this method.

A.2 Sensors protection interface

The results obtained during the preliminary tests on adhesives showed that a protection interface between sensor and soil is necessary. Abrasion resistance tests were performed with an epoxy adhesive patch fixed over the sensor sensing area (Figure A.2).

Figure A.2 Sensors covered with epoxy adhesive patch

The results obtained with this system showed that it provides sufficient protection and the sensors remain fixed to the plough surface. On the other hand, sensibility problems raised due to the stiffness of the epoxy patch. In fact, the rigid substrate created by the patch altered the response of the sensor, previously calibrated in laboratory. In order to have a reliable sensor protection interface that has high abrasion resistance and assure an unmodified sensibility a compound system was designed (Figure A.3).

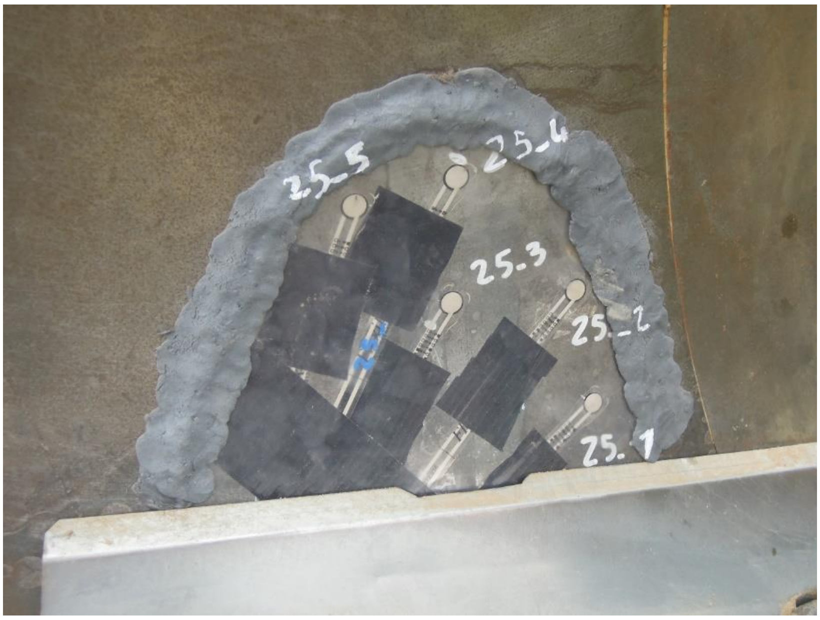

Figure A.3 Compound protection system composed by PVC layer, epoxy resin, polyurethane adhesives and duct tape

Sensors are kept in the correct positions with several stripes of duct tape, then are covered with a 3 mm thick transparent PVC layer. To avoid the detachment of this layer, it has been fixed with polyurethane adhesives on the plough surface. The area of this system most subjected to the soil abrasion action is the contour, so it was strengthened with epoxy resin. Tests demonstrated that the designed system satisfies the objectives in terms of unmodified sensors response, the obtained results are presented in Appendix B. Regarding the abrasion resistance, this system provides the necessary protection only for short measurement because the epoxy resin is quickly eroded by the soil. So, a further improvement of the protection system was the creation of a 2 mm thick welding contour around PVC layer (Figure A.4).

Figure A.4 Improved compound protection system with welding contour

The epoxy resin is still present in order to seal the PVC layer on the plough surface, but its erosion is now slowed down by the welding contour. The results presented in this thesis on the pressure distribution on the plough body were acquired with this version of the protective system.

A.3 Cable protection

As mentioned earlier, even the cables that connect the tactile sensors to the acquisition system have to be protected from the soil abrasive action. The first implemented system consisted in a custom-made metal sheet positioned between ploughshare and mouldboard (Figure A.5).

Figure A.5 Cables protection through a custom-made metal sheet

All the cables coming from ploughshare and mouldboard are collected behind the metal cover, then those are passed in the rear part of the plough where the abrasion is much lower. The cables are properly fixed to the back side of the plough body with abrasion resistance duct tape then passed across the plough beam to the acquisition system positioned in the tractor cab. The results obtained with the tests performed with this solution showed that the designed metal sheet properly protect the cables, but the pressure values measured on the mouldboard were influenced by this cover. In figure A.6 are reported the pressure mean values obtained with a travelling speed of 2 km/h and with a ploughing depth of 0.3 m.

Figure A.6 Pressure mean values [kPa] at 2 km/h speed and 0.3 m ploughing depth

One can note that the measured values on the mouldboard are very low, this is due to the thickness of the metal sheet cover (10 mm) that alters the soil flow over the plough, lowering the pressure on the mouldboard. In order to avoid this disturbance, the metal sheet cover was removed, and a new set up was designed. The protection system showed in figure A.7 is the final version, with which the results presented in this thesis were measured.

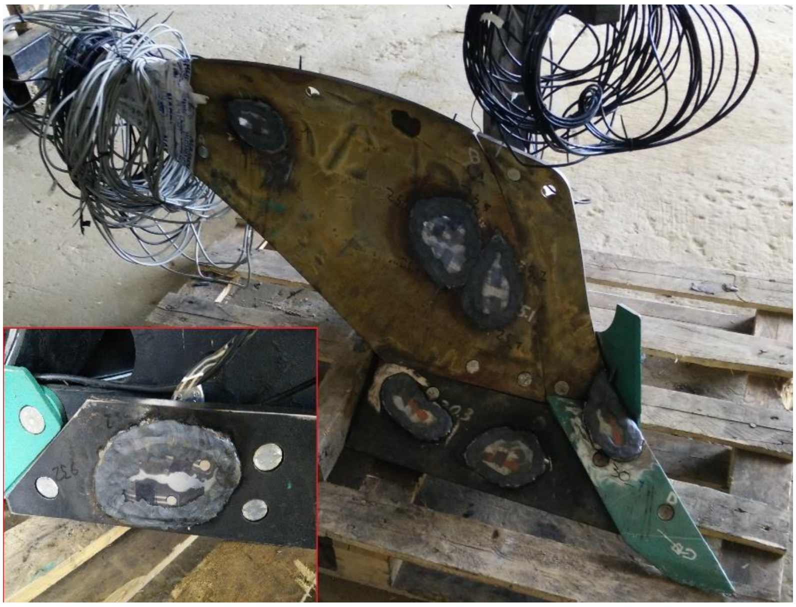

Figure A.7 Protective system final version

In this system the sensors are protected like shown in the chapter A.2, while the cables are passed to the back side of the plough body trough designed holes. The plough surface was drilled in different points located in the nearby of the tactile sensors positions to pass the cables directly on the back side of the plough body. These holes do not affect the soil flow over the plough because those are all located behind the protective PVC layer. Then, the cables are fixed to the back side of the plough body with abrasion resistance duct tape and epoxy resin (Figure A.8).

Figure A.8 Example of cable fixing on the plough body back side

A.4 Future developments

In order to remove completely any possible disturbance of the soil flow over the plough body caused by the adopted protection system, a new type of sensors is going to be installed. The adoption of small diameter, stainless steel pressure sensor permits the design of a new protection system. In Figure A.9 is shown the layout of this new solution.

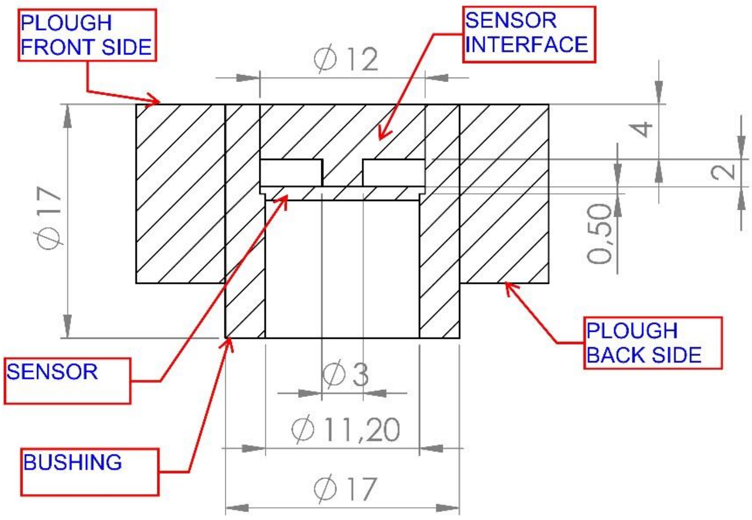

Figure A.9 Section of the new protection system. Dimensions in mm

The sensors are going to be inserted inside custom-made bushings welded into holes created on the plough surface. Between sensors and soil there will be a custom-made steel interface glued directly to the sensors in order to have the correct deformation of the latters.

APPENDIX B

In this appendix are shown the main characteristics of the tactile sensors and the acquisition system used during the tests. Moreover, the results obtained during laboratory tests to investigate the behaviour of the tactile sensors with different protection systems and under different load conditions are reported.

B.1 Tactile sensors and acquisition system

In order to measure the plough-soil pressure ten piezoresistive tactile sensors were used, especially seven FlexiForce A201 (5 on mouldboard and 2 on the wear plate) and three FlexiForce HT201 (on the ploughshare) (Tekscan, Inc., USA). The shape of these two sensors it is the same (Figure B.1) but theirs main characteristics are slightly different (Table B.1).

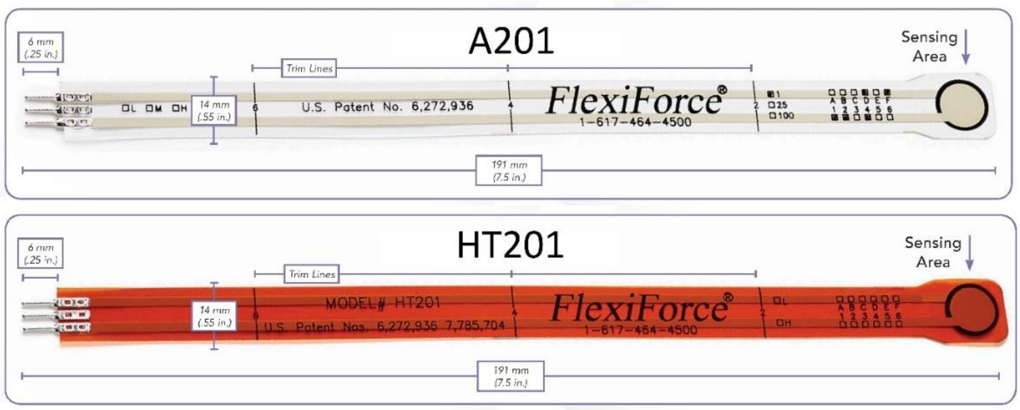

Figure B.1 FlexiForce A201 and HT201 (www.tekscan.com)

Table B. 1 FlexiForce main characteristics

	A201	HT201
Material	Polyester	Polyimide
Operating temperature	-40°C - 60°C	-40°C - 204°C
Sensing area	71.22 mm^2 (Ø 9.53 mm)	71.22 mm^2 (Ø 9.53 mm)
Standard force range	0-111 [N]	0-222 [N]
Standard pressure range	0-1556 [kPa]	0-3112 [kPa]

The sensors output has to be converted into an analogue 0-5 V voltage signal, so each sensor must be connected to a FlexiForce Quickstart Board (Tekscan, Inc., USA). Then, the FlexiForce Quickstart Board output is acquired with a NI 9234 module (National Instruments, USA) mounted on a NI cDAQ 9178 USB data acquisition system (National Instruments, USA). In order to acquire the measured data, a specific LabVIEW (National Instruments, USA) virtual instrument was designed. This virtual instrument is able to record not only the tactile sensors data but even all the output signals from the other sensors installed on the tractor during the tests (GPS and load sensing pins). The acquisition system layout is schematized in Figure B.2.

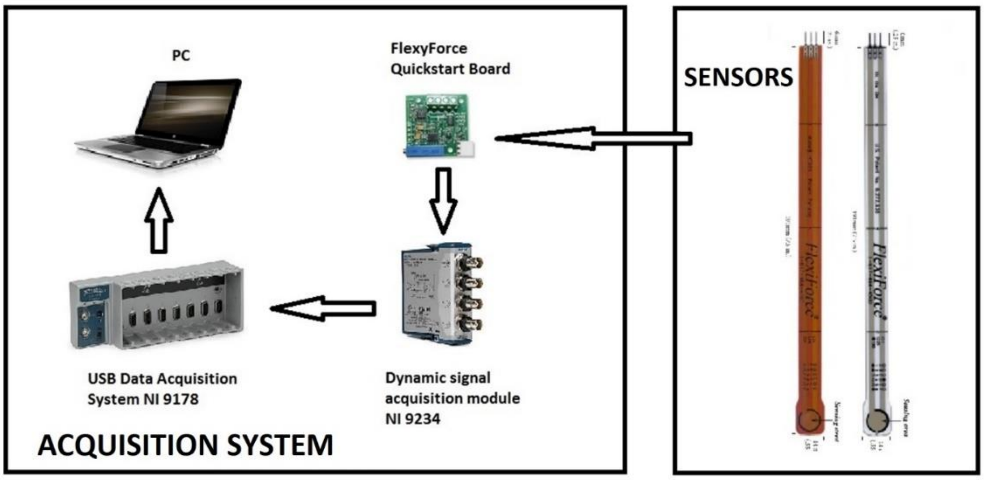

Figure B.2 Acquisition system layout

B.2 Sensors calibration process

Each sensor was calibrated in laboratory before the installation on the plough body. This process was made through a custom-made calibration device, shown in figure B.3.

Figure B. 3 Calibration device

This instrument is composed by a height adjustable steel frame and a precision scale located in the lower side. The input load to apply on the sensor in order to perform the calibration is applied by a screw positioned in a threaded hole on the steel frame. The tip of the screw was properly modified in order to have an area equal to the sensor sensing area. In order to accomplish the calibration, the sensor is positioned between the screw and the precision scale. Then the variation of load, shown on the precision scale, is performed by screwing or unscrewing the screw. Since the sensors have a linear behaviour, the calibration curve was obtained applying 5 input loads equally spaced over the sensors measurement range. In Figure B.4 is shown an example of calibration obtained with a FlexiForce A201 sensor.

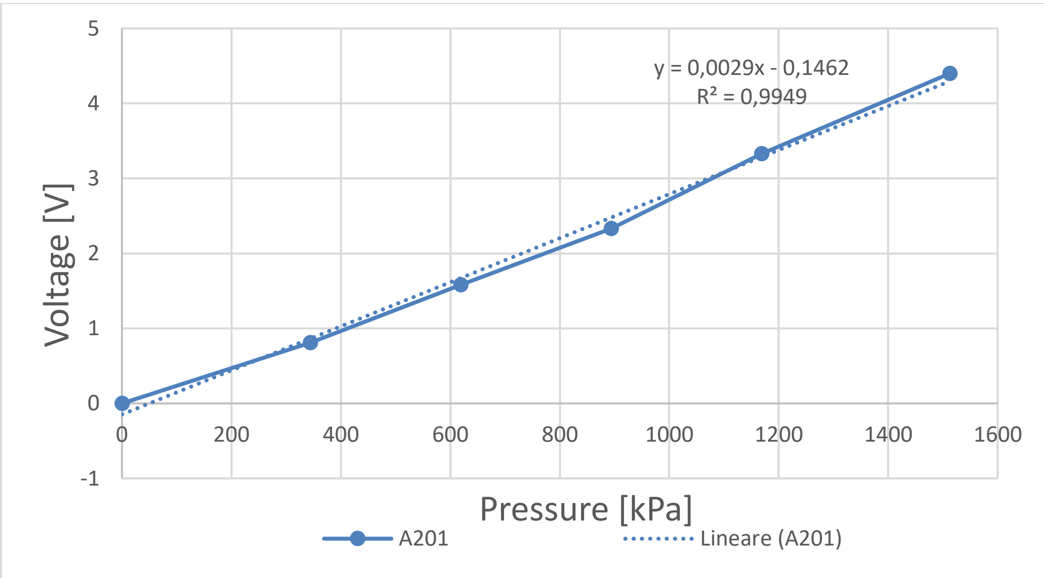

Figure B.4 Calibration curve of a Flexiforce A201. On the x axis there is the input pressure provided by the calibration device, on the y axis the sensor analog output signal (0-5V)

Due to the fact that the sensors have to be protected from the soil abrasion, different protection system were tested to check if the sensor sensibilities are altered. In particular, in Figure B.5 are shown the calibration curves obtained with the two protection systems tested, an epoxy resin patch and an abrasion resistant PVC layer. More details about the chosen protective system are described in Appendix A.

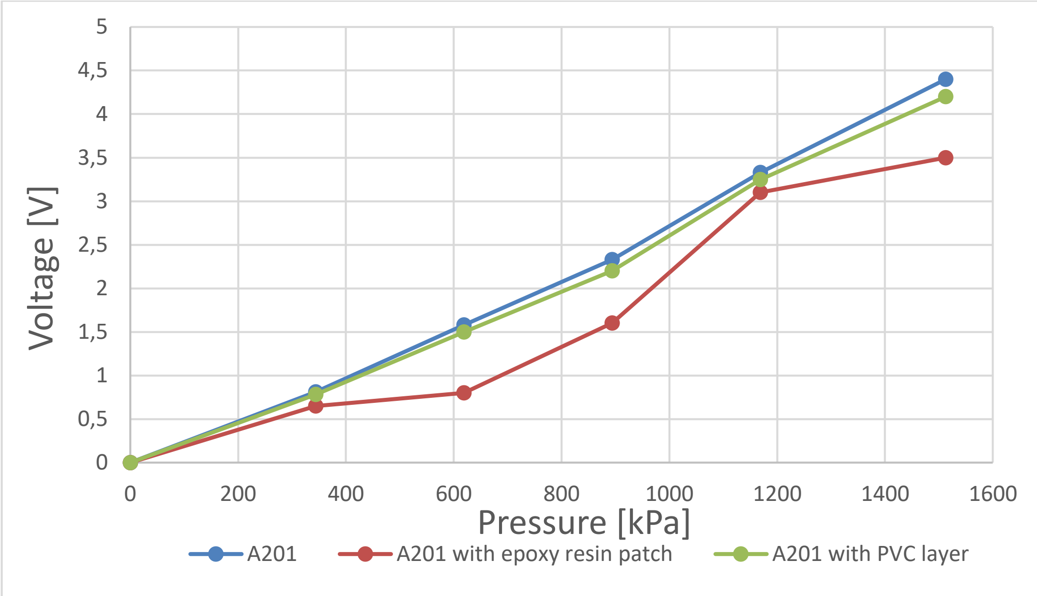

Figure B.5 Calibration curves of a Flexiforce A201 with different protection system. On the x axis there is the input pressure provided by the calibration device, on the y axis the sensor analog output signal (0-5V)

These curves were obtained by recreating the considered protection system in laboratory and then applying the calibration process described earlier (Figure B.6).

Figure B.6 PVC layer protective system testing method

One can note that the sensibility of the sensor protected with the epoxy resin patch is strongly altered, while with the PVC layer there aren't significant changes. In fact, the obtained coefficients of determination (R^2) for the sensor without protection, with the epoxy resin and with the PVC layer are respectively 0.9949, 09934 and 0,9362. Each tactile sensor was calibrated in laboratory with the PVC layer protection, in order to reproduce more closely the protective system implemented on the plough.

B.3 Repeatability of the measure

In order to evaluate the repeatability of the measure a cyclic test procedure was carried out. It consists in applying the same load on a FlexiForce A201 sensor 10 times, with a time gap between two repetitions of 1 minute. The three considered load conditions are the 10%, the 50% and the 100% of the sensor full-scale. The obtained results are showed in Figure B.7.

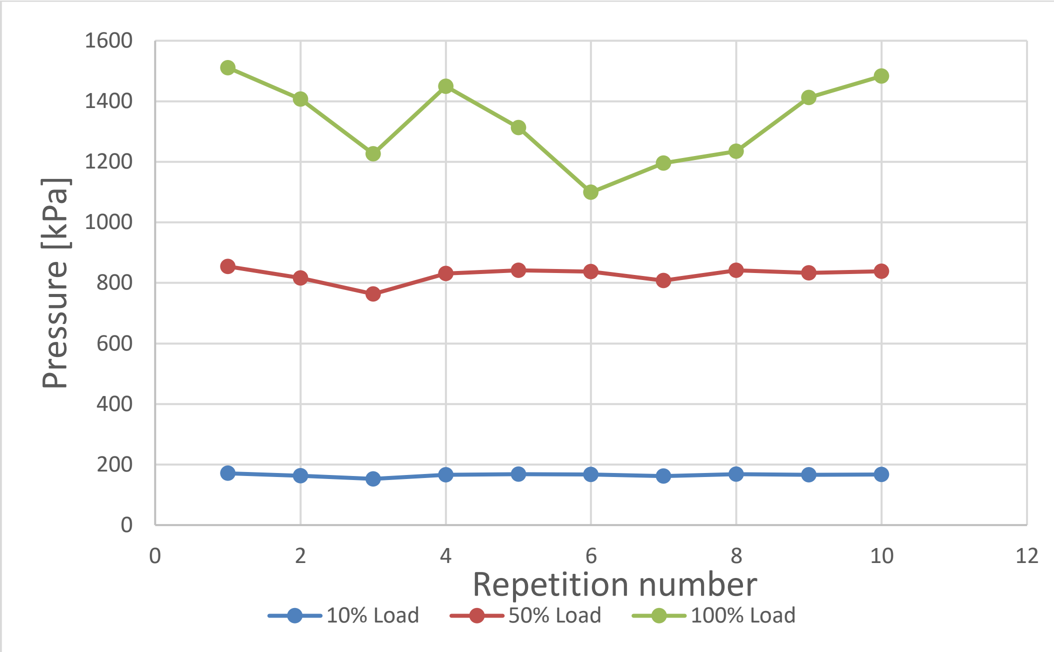

Figure B.7 Repeatability of the measure test. On the x axis there is repetition number, on the y axis the sensor measured pressure

The results show that there is a good repeatability with the 10% and the 50% of the sensor full-scale load, in fact the obtained standard deviations are around the 3% of their mean values. With the load fixed to the 100% of the sensor full-scale, the repeatability worsens and the standard deviations is the 10% of the mean value.

B.4 Sensor drift

To evaluate the drift of the tactile sensors used to measure the pressure distribution on the plough body, a FlexiForce A201 was charged with the 50% of its full-scale load for 65 minutes. The pressure value was acquired every 5 minutes and the results are shown in Figure B.8.

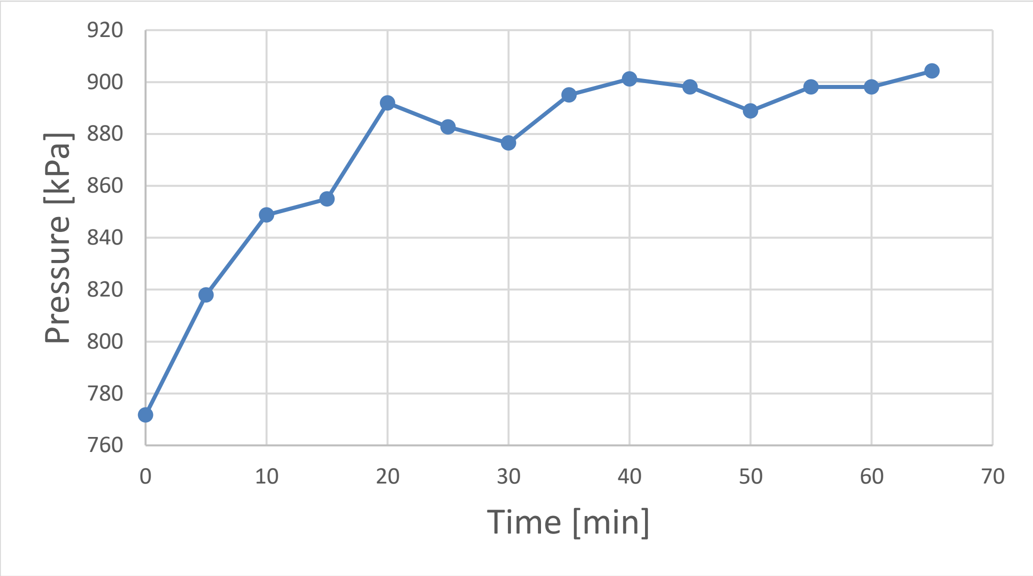

Figure B.8 Sensor drift test. On the x axis there is time, on the y axis the sensor measured pressure

In the first 20 minutes of the tests the sensor showed a strong drift, in fact the pressure value measured at the end of this time frame is 15% higher than the starting value. Then, after this time frame the sensor has a more constant behaviour, indeed the fluctuations of the measured pressure are around 2%.

B.5 Sensor response in relationship with granulometry

In order to evaluate if the soil granulometry could influence the sensibility of the sensor a test with steel spheres was carried out. A 30 mm diameter cylindrical tube was positioned over the sensor sensing area, then filled with several 3 mm diameter steel spheres. Then a steel disc with the same diameter of the tube was positioned on top to permit the input of the load through the screw of the calibration device (Figure B.9). This test was performed with the PVC layer protection in order to reproduce more closely the plough testing condition.

Figure B.9 Granulometry test layout, the steel disc was positioned over the steel spheres during the test

In Figure B.10 the measured values are compared with the calibration curve of the same sensor without the spheres interface.

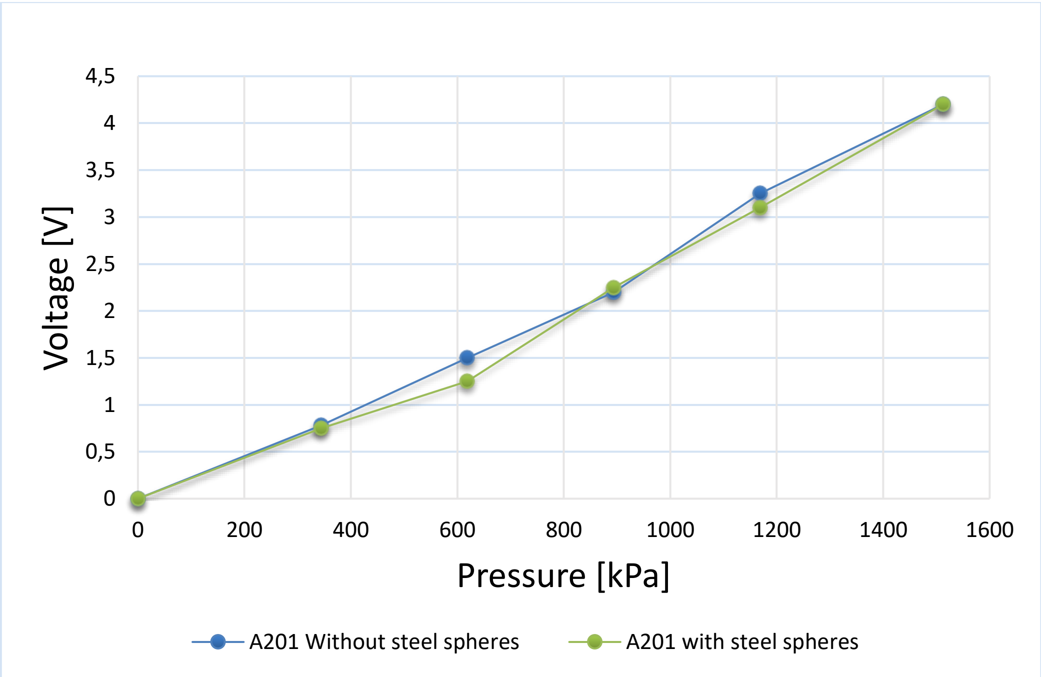

Figure B.10 Output signals of a Flexiforce A201 with and without the steel sphere interface. On the x axis there is the input pressure provided by the calibration device, on the y axis the sensor analog output signal (0-5V)

One can note that the sensibility of the sensor is not significantly affected by the steel spheres, the obtained R^2 for the sensor without spheres and the sensor with the spheres are respectively 0.9934 and 0,9877. This is due to the fact that the PVC layer inserted between the spheres and the sensor distributes the pressure almost equally on the sensor sensing area, smoothing possible pressure peaks caused by the sphere contact surface.

La lista di persone da ringraziare per avermi supportato (o sopportato?) durante il mio periodo di dottorato è molto lunga, ma cercherò di non dimenticare nessuno.

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