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Discrete element analysis for the assessment of the accuracy of load cell-based dynamic weighing systems in grape harvesters under different ground conditions

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ABSTRACT

Dynamic weighing systems based on load cells are commonly used to estimate crop yields in the field. There is lack of data, however, regarding the accuracy of such weighing systems mounted on harvesting machinery, especially on that used to collect high value crops such as fruits and vegetables. Certainly, dynamic weighing systems mounted on the bins of grape harvesters are affected by the displacement of the load inside the bin when moving over terrain of changing topography. In this work, the load that would be registered in a grape harvester bin by a dynamic weighing system based on the use of a load cell was inferred by using the discrete element method (DEM). DEM is a numerical technique capable of accurately describing the behaviour of granular materials under dynamic situations and it has been proven to provide successful predictions in many different scenarios. In this work, different DEM models of a grape harvester bin were developed contemplating different influencing factors. Results obtained from these models were used to infer the output given by the load cell of a real bin. The mass detected by the load cell when the bin was inclined depended strongly on the distribution of the load within the bin, but was underestimated in all scenarios. The distribution of the load was found to be dependent on the inclination of the bin caused by the topography of the terrain, but also by the history of inclination (inclination rate, presence of static periods, etc.) since the effect of the inertia of the particles (i.e., representing the grapes) was not negligible. Some recommendations are given to try to improve the accuracy of crop load measurement in the field.

1. Introduction

In the 1990s, a number of authors studied the use of grain mass flow sensors in combine harvesters (normally placed at the top of the grain elevator) as a means of generating yield maps (Colvin et al., 1991; Stafford et al., 1991; Vansichen and De Baerdemaeker, 1991). The production of such maps requires the interpolation of instantaneous grain yields in order to estimate the average for a given area (Birrell et al., 1996). Unfortunately, the sensors used in combine harvesters are usually unsuitable for use with other types of crop. Indeed, very few yield monitoring systems are commercially available for use with fruits and vegetables (Durrence et al, 1999; Pelletier and Upadhyaya, 1999; Magalhães and Cerri, 2007; Maja and Ehsani, 2010). The solution in many cases has been to use load cells to weigh the collected crop.

Durrence et al. (1999) developed a load cell-based yield monitor for peanut harvesters. Capacity load cells were fitted to the bin supports, and cumulative weights were recorded. Pelletier and Upadhyaya (1999) designed a load cell-based yield monitor for tomato crops. These authors decided to use a belt weigher for making load measurements, locating load cells in the last section of the boom elevator (just before the fruit is delivered to the truck). Miller and Whitney (1999) and Whitney et al. (2001) calculated the yield of citrus fruits using three different systems: a pressure transducer in the pressure line of a truck bed lifting system, four load cells under a truck bed, and a single load cell in a loader boom. Maja and Ehsani (2010) developed a yield monitoring system for citrus fruit mechanical harvesting involving a load cell-based impact plate. The system was modelled using either combinations of loads, springs and dampers, or using the energy balance equation. During field testing, the plate was installed at the end of the harvesting machine's fruit conveyor belt.

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The Pellenc S.A. company (Pellenc and Bourely, 2001) developed a dynamic weighing system for grape harvesters in which grape clusters are weighed by two sets of load cells before they reach the collection bin. Arnó et al. (2005) tested another grape-weighing system involving a yield monitor and load cells located on the lateral discharge conveyor belt. Baguena (2011a) developed an on-board dynamic weighing system for grape harvesters, with load cells located directly under the bin. The main advantage of this is that the proper working of the system can be quickly verified. In this system, weight measurement is cumulative rather than instantaneous.

It is extremely important that the possible sources of error in yield monitoring systems be understood and taken into account. Blackmore and Marshall (1996) and Blackmore and Moore (1999) reported the effect on yield maps of errors associated with the topography of the terrain, volumetric calibration, unknown crop width on entry to the header, harvester fill mode, incorrect lag time, digital GPS (Global Positioning System) accuracy, and yield sensor accuracy. They concluded that the quality of data collected can be improved through the use of appropriate filters.

Although load cells may be certified for use in dynamic weighing systems, they are not error-free. The correction of the problems giving rise to these errors is an important area of sensor research. Makabe and Kohashi (2007) reported load cell errors such as hysteresis and creep owed to the design of the active part of the sensor. Hysteresis can be the consequence of the design a load cell and the properties of the materials used to make it. Improvements might therefore be obtained by constructing load cells with more appropriate materials. Hysteresis compensation methods have also been proposed (Makabe and Kohashi, 2004; Zijian and Renwen, 2002).

The topography of the terrain (the slope of fields) over which a harvester must move can cause errors in load cell measurements. In the laboratory, Fulton et al. (2009) subjected a combine harvester equipped with a yield monitor and a mass flow sensor (i.e., with no load cell) to different inclinations. Both transversal and especially longitudinal inclinations (0–8.5°) influenced the results returned by the weighing system. This same conclusion was reached by Baguena et al. (2011b), who examined the effect of inclination on an on-board dynamic weighing system that *did* involve load-cell measurements. The error was small when the machine was tested in the horizontal position – the natural orientation for its calibration – but became large at the most extreme inclinations. Both sets of authors suggested a compensation formula for minimising the effects of inclination.

Recently the discrete element method (DEM, Cundal and Strack, 1979) has been shown to predict the behaviour of moving granular material very well (Van Zeebroeck et al., 2006; Van Liedekerke et al., 2009; Ramírez et al., 2010a, 2010b; González-Montellano et al., 2011, 2012; Balevičius et al., 2011; Kobyłka and Molenda, 2013). In the present work, the DEM was used to simulate the displacement of the load inside a grape harvester bin in relation to its inclination. Different DEM models were developed, inclining the grape harvester forward and backward several times to reproduce changing terrain conditions. The redistribution of the load in the bin was shown to affect the results that would be provided by load cells under the bin. Recommendations to improve the accuracy of load cell measurements made in the field are proposed.

2. Materials and methods

2.1. Models

The DEM models constructed simulated the behaviour of the material in the bin of a classic grape harvester. Fig. 1 shows the shape of the bin, the walls of which are made of steel sheeting. Given the recommendations provided in the literature, the use of a load cell is assumed, located on a beam under the bin. The load cell estimates the mass of the material stored in the bin. The front of the bin is assumed to contain a hydraulic cylinder (Fig. 1a) to incline – and thus empty – the bin on demand.

Hydrogel spheres were used to represent grapes. This facilitated validation tests of the models – hydrogel spheres are neither perishable nor subject to seasonal availability. The mechanical properties of grapes and hydrogel spheres were assumed to be very similar.

All simulations were performed using EDEM Academic v2.3 (2010) software. In all cases, the interactions between particles and between particles and walls were represented by the Hertz–Mindlin contact model (Mindlin, 1949; Tsuji et al., 1992; Džiugys and Peters, 2001; Balevicius et al., 2006). Although grapes are not simple elastic bodies, this elastic, non-linear contact model is considered to be a good enough approximation for the purposes of this work. With the aim of taking into account energy dissipation in the system, viscous damping was contemplated in the normal and tangential directions for each contact, plus frictional damping in the tangential direction. The time step (Δ_t) in all simulations was constant at 1.47×10^{-4} s, i.e., at 20% of the critical time pass (Δ_{tc}) given by the Rayleigh time (t_R) (Li et al., 2005).

Values for the mechanical properties of the hydrogel spheres (Table 1) were determined experimentally when possible. Standardised, validated procedures were followed whenever available. When not, procedures proposed in the literature were used if possible; when no reliable procedure was available, values were fixed in agreement with the experience of the authors and modified if needed in accordance with the model validation process (Section 3.1).

In all models, the hydrogel spheres were represented as spherical particles of non-uniform size in agreement with the results of preliminary analyses of the real spheres. A normal size distribution was assumed, based on a mean diameter of $d = 8.85$ mm ($\sigma = 1.30$ mm). In order to simulate a more real situation, and to avoid instabilities in simulations owed to the presence of oversized or undersized particles (González-Montellano et al., 2011), the normal size distribution used was limited to $d_{min} = 0.85$d, and $d_{max} = 1.15$d.

2.2. Models constructed and simulation procedure

The simulation procedure followed for all DEM models involved two stages: a filling or static stage, and a dynamic stage. The filling stage was short, starting with the creation of the particles at some point inside the bin (which remained still throughout this stage) and ending with the pile of particles resting over the bottom of the bin. The generation of the particles was initiated at a virtual rectangular surface (Fig. 1b) located in the upper part of the bin. In fact, two such virtual surfaces were contemplated: VS1, which was smaller and located close to the front of the bin, and VS2, which was larger and covered the entire free surface of the bin. Both surfaces were deemed to be at a height $Z = 0.9$ m according to the reference system provided in Fig. 1. The particles were generated from these virtual surfaces in two ways: (1) by constant generation, in which particles are created continuously at a fixed generation rate (GR) until the final mass (W) of the particles is reached and (2) by discrete generation, in which W is fractionated into several parts with each part being created at regular times at a fixed generation rate (GR). The use of VS1 is aimed at establishing an initial particle distribution concentrated towards the front of the bin. In contrast, VS2 is used for generating an initially uniform distribution of particles. The use of one or the other virtual surface