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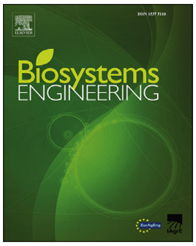

Research Paper

Sensor for monitoring rice grain sieve losses in combine harvesters

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Grain sieve losses are important parameters to judge the performance of cleaning shoes in combine harvesters. To keep grain sieve loss within acceptable limits, an impact-type piezoelectric sensor was developed for real-time monitoring. Rice grain and short straw particle models were established according to their physical properties, and discrete element method (DEM) simulations were carried out to understand their collision behaviour with the sensor. The influence of grain shape, straw length and impact angle on variations of the maximum normal contact force and force rise-time were analysed in detail. Differences in normal collision force, and force rise-time occurred which lead to corresponding differences in signal frequency and voltage amplitude. A signal processing circuit, which mainly consisted of a band-pass filter circuit and a voltage comparator circuit, was designed to discriminate for full grains. Field tests results indicated that measurement errors recorded by the sensor and checked against manually measurements were <4.48%.

1. Introduction

Combine harvesters operate all over the world, harvesting different crops under different environmental conditions. They have functions which cover the entire harvesting process that can be divided into cutting, threshing, separating, cleaning and storing. Cleaning process, refer to the final separation of grain from material other than grain (MOG), which is influenced by a wide range of parameters including crop yield, climate, threshing and cleaning settings (Craessaerts, De Baerdemaeker, Missotten, & Saeys, 2010; Craessaerts, Saeys, Missotten, & Baerdemaeker, 2010). Grain sieve loss, which is influenced by a wide range of parameters such as design, operating conditions as well as crop properties, is an important parameter to judge the performance of the cleaning shoe. In China, evaluation of grain sieve losses mainly relies on manual labour, using a canvas to collect all mixed material at the exhaust port, then filtering out the grains from MOG by a re-cleaner, weighing them and then calculating the absolute sieve loss. This value can be used for benchmarking, but it cannot be used for system control because it cannot be obtained real-time. With the advances in sensors and automation in recent years, researchers have proposed many sensors for use with combine harvesters to extract real-time information from the working process (Craessaerts, Saeys, Missotten & De Baerdemaeker, 2008; Omid, Lashgari, & Mobli, 2010; Reyns, Missotten, Ramon, & Baerdemaeker,

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Nomenclature

a,b	semi-axis lengths of ellipsoid, m
C	equivalent capacitance, F
C_a	capacitance in piezoelectric ceramics, F
C_c	cable capacitor, F
C_i	input capacitance, F
d_{31}, d_{33}	piezoelectric constant, PC/N
e	coefficient of restitution
E^*	effective Young's modulus, MPa
E_1	Young's modulus of grain, MPa
E_2	Young's modulus of sensor, MPa
$\mathbf{F_n}$	normal contact force, N
$F_{n\ max}$	maximum normal impact force, N
$F_{n1\ max}$	grain maximum normal impact force, N
$F_{n2\ max}$	straw maximum normal impact force, N
$\mathbf{F}_\tau$	tangential contact force, N
$F_{\tau1\ max}$	grain tangential contact force, N
$F_{\tau2\ max}$	straw tangential contact force, N
F_n^d	normal damping force, N
F_τ^d	tangential damping force, N
$\mathbf{g}$	gravitational acceleration, m s^{-2}
G^*	effective shear modulus, MPa
G_1	shear modulus of seed, MPa
G_2	shear modulus of sensor, MPa
K_{33}	electromechanical coupling coefficient
I	moment of inertia, kg m^2
m	mass of grain, g
m^*	equivalent mass, g
$\mathbf{n}$	contact normal vector
p	contact pressure, MPa
p_y	yield pressure, MPa
Q_m	mechanical quality factor
r	loss grains ratio
R	rotating radius of particle, m
R_1, R_2	radii of principal curvature, m
R^*	mean effective radius, m
R_i	input resistance, Ω
t_i	collision time, s
t_{i1}	grain collision time, s
t_{i2}	straw collision time, s
t_r	force rise-time, s
t_{r1}	grain impact force rise-time, μs
t_{r2}	straw impact force rise-time, μs
T_c	curie temperature, °C
Tr_3	relative permittivity
U_{max}	voltage amplitude, V
$\mathbf{U}$	unit vector of rotating shaft
$\mathbf{v}$	vector of particle velocity, m s^{-1}
v_n	normal velocity, m s^{-1}
v_{n1}	grain normal velocity, m s^{-1}
v_{n2}	straw normal velocity, m s^{-1}
$\mathbf{v}_\tau$	tangential velocity, m s^{-1}
$v_{\tau1}$	grain tangential velocity, m s^{-1}
$v_{\tau2}$	straw tangential velocity, m s^{-1}
v_n^{rel}	normal relative velocity, m s^{-1}
v_τ^{rel}	tangential relative velocity, m s^{-1}
δ_n	normal overlaps, m
δ_{n1}	grain normal overlaps, m
δ_{n2}	straw normal overlaps, m
δ_τ	tangential overlaps, m
$\delta_{\tau1}$	grain tangential overlaps, m
$\delta_{\tau2}$	straw tangential overlaps, m
α	normal overlap, m
α_{max}	maximum normal overlap, m
α_y	yield overlap, m
γ	aspect ratio
V_{out}	collision output voltage, V
V_{out1}	grain collision output voltage, V
V_{out2}	straw collision output voltage, V
ν_1	Poisson's ratio of output material
ν_2	Poisson's ratio of plate
θ_1	grain impact angle, (°)
θ_2	straw impact angle, (°)
η_1	grain peak force ratio
η_2	straw peak force ratio
$\boldsymbol{\omega}$	rotational velocity, rad s^{-1}
ρ_m	density, g cm^{-3}
DEM	discrete element method
MCU	microcontroller unit
MOG	material other than grain
PVDF	polyvinylidene fluoride

2002), either by monitoring machine settings (e.g. driving speed, fan speed, upper and lower sieve opening) (Mcgechan, 1982), machine load (e.g. feed-rate, torque drum, engine load and grain mass flow) (Loghavi, Ehsani, & Reeder, 2008) or by measuring field-related parameters (e.g. moisture content of grain, machine lateral and longitudinal inclination) (Craessaerts, De Baerdemaeker et al., 2010; Craessaerts, Saeys et al., 2010; Lenaerts, Missotten, De Baerdemaeker, & Saeys, 2012; Mouazen, Anthonis, & Saeys, 2004). Some researchers also have engaged in grain sieve loss auto-detection technology (Hiregoudar, Udhaykumar, Ramappa, Shreshta, & Medaet, 2011) and many advanced combine harvesters have grain sieve loss monitoring sensors installed (Eldredge, 1985; Liu and Leonard, 1993; Zhou, Zhang, Liu, & Yuan, 2010; Gao, Zhang, Yu, & Li, 2011; Li, 2006; Ni, Mao, & Tian, 2011; Osselaere, 1985). To date, a measure was found for monitoring grain loss by quantifying grain impacts during a fixed interval based on piezoelectric effect. However, the combine harvesters produced in Europe and North America are mainly used for harvesting crops, such as wheat, bean and oil-seed rape. Rice, one of the most important crops in China, is very different in its physical properties to these crops and there is therefore a need to develop a signal processing circuit to accurately discriminate rice grain loss from MOG.

The surface of grain sieve loss monitoring sensors usually consists of a rigid plate. Different materials collide with the plate causing differences in the frequency and force of the collision. The impact behaviour of grains and MOGs with the plate is therefore a critical step for designing a signal processing circuit for real-time monitoring. In recent years,