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Automatic starting control of tractor with a novel power-shift transmission

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ABSTRACT

In this paper, a novel power-shift transmission using hydro-viscous drive (HVD) technology is proposed to improve starting comfort without affecting the drivetrain service life of a tractor. The tractor equipped with this novel power-shift transmission can realize stepless speed-regulation crawling. The structure of the tractor drivetrain, transmission scheme, gear ratios, and parameters of the HVD device are designed based on the operation requirements. The dynamical model of the drivetrain for tractor starting is established, and the control strategy for automatic starting of the tractor is developed to match this novel power-shift transmission. To verify the availability and effectiveness of this novel transmission in tractor automatic starting, a simulation model is established and the automatic starting processes under various driver's intentions are simulated. Accordingly, the simulation results show that this novel power-shift transmission cooperated with reasonable automatic control strategy can achieve a better starting effect. The tractor can realise 'soft starting' with small jerk as well as high comfort under starting intention of the driver. Moreover, the HVD device only works in the stage of hydro-viscous friction, which can prevent the failure of transmission caused by large temperature increase and contact friction.

1. Introduction

With the development of precision agriculture [1], tractors, as the main power machinery for field operations, are rapidly developing towards high performance and intellectualization [2]. As an important part of the vehicle system, the drivetrain is one of the main objects of focus and is designed and optimised by researchers and manufacturers.

Most studies to design and optimise the transmission gearbox focus on improving the performance and efficiency of the drivetrain during regular operation. Rotella et al. [3,4] provided a model for the preliminary design of compound power-split continuously variable transmissions and a fast kinematic analysis method for this kind of transmission. Xia et al. [5] proposed a new continuously variable transmission system for the purpose of improving the transmission efficiency in vehicles. Molari et al. [6] tested and analysed the power losses in a power-shift transmission of tractor under a variety of conditions. Chen et al. [7] designed a novel wheel-type continuously variable transmission and analysed its efficiency.

With the increasing demand for control precision and comfort during tractor starting, it is very important to improve the starting performance of the tractor transmission. The tractor equipped with power-shift transmission starts mainly by the sliding friction of clutch [6,8]. However, there is a conflict between the degree of jerk and friction work when the vehicle

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Nomenclature

a, a_{cb_tar}	vehicle acceleration, target angular acceleration of clutch driven disk
A_p	plate area
f	coefficient of rolling resistance
F_a, F_d, F_i, F_j	air resistance, draft requirement, slope resistance, accelerating resistance
F_r, F_p, F_q	external resistance of tractor, shear force of oil film, required driving force
g	gravity
i_f, i_h, i_m	transmission ratios of forward gear pair, gear pair for HVD device and main reducer
i_p, i_s, i_w	transmission ratios of power-shift gearbox, synchronised range gearbox and wheel reducer
I_f, I_w	inertial moment of engine flywheel, inertial moment of wheels
i_{pL}, i_{pM}, i_{pH}, i_{pS}	transmission ratios of gear L, gear M, gear H and gear S in power-shift gearbox
m, m_1, m_2	tractor-implement combination mass, tractor mass, farm tools mass
n_e	engine speed
N_{init}, N_{tar}	initial transmission gear, target transmission gear
r	wheel radius
R_e, R_{y1}, R_{y2}	surface roughness of dual disk, maximum heights of dual disk surface profiles
T_c, T_e, T_{e_max}	clutch torque, engine torque, maximum engine torque
T_h, T_{h_max}, T_{h_crit}	torque of HVD device, maximum torque of HVD device, torque of HVD device at critical point
v	tractor speed
Z	quantity of oil films
z_R, z_S	numbers of teeth in ring gear and sun gear
β, β_{init}, β_{tar}	throttle opening, initial throttle opening, target throttle opening
δ, δ_{min}	thickness of liquid (oil) film, allowed minimum thickness of oil film
Δv_p	relative velocity between plates
$\Delta\omega_c$	angular velocity difference between driving disk and driven disk of clutch
$\Delta\omega_{h\_ave}$,	average angular velocity difference between driving and driven disks of HVD device
$\Delta\omega_{h\_max}$	maximum angular velocity differences between driving and driven disks of HVD device
$\Delta\omega_{h\_min}$	minimum angular velocity differences between driving and driven disks of HVD device
η_1	mechanical efficiency of subassembly from HVD device to wheels
η_2	mechanical efficiency of subassembly from engine to HVD device
η_t	mechanical efficiency of driveline
λ	correction coefficient of the rotating mass
μ	dynamic viscosity of fluid (oil)
τ	shear stress of oil film
ω_e, ω_{ca}, ω_{cb}	angular velocities of engine, clutch driving disk and clutch driven disk
ω_{ha}, ω_{hb}	angular velocities of HVD device driving disk and HVD device driven disk

starts using a friction clutch [9]. If the clutch engages too suddenly, a large starting jerk and high fluctuation of engine torque will be generated, which affects comfort and may cause engine stalling. On the contrary, if a smooth engagement is pursued, and the engaging speed is overly reduced, the friction work that is caused by the sliding friction between driving and driven disks of clutch in engaging process would be great [10]. Large amounts of heat are produced, which raises the surface temperature sharply, which in turn may cause steel disk deformation, burning, or even scuffing or lubricating oil failure. In addition, the useful lifetime of the clutch would be shortened [11,12]. Many studies on the thermal behaviour, wear behaviour, and engagement process of friction clutch have been conducted [11–17]. However, the conflict between the comfort and the service life of the friction clutch cannot be completely and fundamentally resolved.

Because of the high mass and inertia of the tractor-implement combination, the high travel resistance, and the characteristic of starting under high gear, the sliding friction time of clutch in the starting process is much longer than that of road vehicles [18]. However, in order to protect the clutch and lubricant oil of power-shift transmission in field operations with frequent starting, starting comfort must be sacrificed in most cases. In addition, the tractor need to reasonably regulate its speed and maintain a very low speed when it adjusts its position to engage the agricultural implement or moves within a narrow space. The creeper gears have to be increased in traditional power-shift transmission to avoid the extended period sliding friction of clutch at lower speed conditions.

To solve the aforementioned problems, in this study, the hydro-viscous drive (HVD) technology, which has the advantage of soft starting for equipment, is applied to design a novel power-shift transmission for tractors. As a type of stepless speed-regulation technology, the HVD technology has been used successfully in belt conveyors, pumps and other high-power and heavy-duty machines [19–21]. When the HVD device works in the stage of hydro-viscous friction, the multidisk pairs do not contact directly. Owing to the existence of complete oil films between the dual disks, the heat generated in operation can