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A DOPPLER RADAR SLIP MONITOR FOR TRACTION EQUIPMENT

by

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ABSTRACT

The feasibility of monitoring drive-wheel slip of agricultural traction devices by microwave Doppler radar was investigated. Technical and economic feasibility of using a Doppler radar slip monitor to maximize power efficiency and limit tire wear from excessive slip were evaluated.

The Doppler radar slip monitor is based on application of Doppler radars to continuously sense the ground velocity of the tractor and the circumferential velocity of the drive wheel. The difference between ground and circumferential velocities normalized to the circumferential velocity is equal to the dynamic slip. A technique of monitoring the angular velocity of the drive wheel, and measuring the ground velocity of the tractor using a fifth wheel assembly was utilized as a conventional method.

All electrical signals during the field tests were recorded by battery operated magnetic tape recorders and were subsequently analyzed in the laboratory by an analog system and by a digital computer. The slips measured by Doppler radars are in good agreement with those measured by the conventional method.

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f_d - Doppler frequency

f_{GL} - Frequency of the Doppler signal from the ground when the tractor is loaded.

f_{GN} - Frequency of the Doppler signal from the ground at no load condition.

f_M - Frequency of the microswitch pulses.

f_{ML} - Frequency of the microswtich pulses when the tractor is loaded.

f_{MN} - Frequency of the microswitch pulses at no load condition.

f_o - Frequency of transmission.

f_{TL} - Frequency of the Doppler signal from the tire when the tractor is loaded.

f_{TN} - Frequency of the Doppler signal from the tire at no load condition.

f_W - Frequency of the signal from the fifth wheel assembly.

f_{WL} - Frequency of the signal from the fifth wheel assembly when the tractor is loaded.

f_{WN} - Frequency of the signal from the fifth wheel assembly at no load condition.

h - Height of the source above the scattering surface.

N - Number of statistically independent samples taken in a period of time, T.

R - Rolling radius of the tractor drive wheel.

R_W - Rolling radius of the fifth wheel.

S - Slip

S_C - Slip measured by the conventional method.

S_D - Slip measured by two Doppler radars.

S_{MD} - Slip measured by one Doppler radar and the microswitch assembly.

T - Period of time.

V - Velocity of the vehicle.

V_G - Ground velocity of the tractor.

V_T - Circumferential velocity of the tractor drive wheel.

V_W - Circumferential velocity of the fifth wheel.

X - Average chart distance at no load condition.

Y - Chart distance when the tractor is loaded.

Δf_d - Spectral spread due to the divergence of the antenna beam.

Δf_s - Spectral spread due to scanning of the antenna beam.

$\Delta\theta$ - Two-way 3-dB antenna beam width.

δf_d - Uncertainty in the measurement of the Doppler frequency.

δf_{GL} - Uncertainty in the measurement of the frequency of the Doppler signal from the ground when the tractor is loaded.

δf_{GN} - Uncertainty in the measurement of the frequency of the Dopper signal from the ground at no load condition.

δf_{ML} - Uncertainty in the measurement of the frequency of the microswitch pulses when the tractor is loaded.

δf_{MN} - Uncertainty in the measurement of the frequency of the microswitch pulses at no load condition.

δf_o - Uncertainty in the frequency of transmission.

δf_{TL} - Uncertainty in the measurement of the frequency of the Doppler signal from the tire when the tractor is loaded.

δf_{TN} - Uncertainty in the measurement of the frequency of the Doppler signal from the tire at no load condition.

δf_W - Uncertainty in the measurement of the frequency of the magnetic pickup signal.

δf_{WL} - Uncertainty in the measurement of the frequency of the magnetic pickup signal when the tractor is loaded.

δf_{WN} - Uncertainty in the measurement of the frequency of the magnetic pickup signal at no load condition.

δR_W - Uncertainty in the measurement of the rolling radius of the fifth wheel.

δS - Uncertainty in the slip measurement.

δS_C - Uncertainty in the slip measurement by the conventional method.

δS_D - Uncertainty in the measurement of slip by Doppler radars.

δS_{MD} - Uncertainty in the slip measurement by one Doppler radar and the microswitch assembly.

δV - Uncertainty in the velocity measurement.

δV_G - Uncertainty in the measurement of the ground velocity of the tractor.

δV_T - Uncertainty in the measurement of the circumferential velocity.

δV_W - Uncertainty in the velocity measurement by the fifth wheel.

δX - Uncertainyy in the measurement of the average value of the chart distance at no load condition.

δY - Uncertainty in the measurement of the chart distance when the tractor is loaded.

$\delta\theta$ - Uncertainty in the measurement of the viewing angle.

θ - Antenna viewing angle.

θ_G - Viewing angle of the antenna directed towards the ground.

θ_T - Viewing angle of the antenna directed towards the tire.

λ - Transmitted wavelength.

σ_d - Standard deviation which includes both the scanning noise and the fluctuation noise.

$\sigma_{d,T}$ - Standard deviation of the average value of the Doppler frequency which is smoothed or averaged over a period of time, T.

σ_{f_d} - Standard deviation of the fluctuation noise.

σ_{f_s} - Standard deviation of the scanning noise.

τ_f - Correlation time.

ω_R - Uncertainty in a given function R of independent variables $x_1, x_2, x_3, \ldots\ldots\ldots\ldots, x_n$.

CHAPTER I

INTRODUCTION

Slip[1] or travel reduction occurs when agricultural traction devices[2] pull a drawbar load. Various studies have been made in an effort to control drive-wheel slip of agricultural tractors below some arbitrary limit. Most tractor operators would probably consider the arbitrary limit to be 30 percent.

Reducing or controlling slip of traction devices for agricultural machinery would conserve energy. Not only would there be a saving of energy but there could be savings in tire wear and in capital costs. For the same expenditure of mechanical energy per unit area it can be shown that a 2 percent increase in tractive efficiency could reduce overall fuel comsumption by approximately 1 percent (Townsend, J.S. 1975, private communication). In these times of energy shortages any method of conserving energy should not be ignored.

Tractor operators need a simple method for determining the amount of traction device slip under field conditions. Slip should not be excessive in order to obtain maximum tractive efficiency and to reduce tire wear. Generally maximum tractive efficiency occurs when the driving wheels slip between 10 and 15 percent (Barger et al., 1963). Tractive efficiency will be reduced from the maximum value expected if slip is too low or too high. Proper ballasting of tractors or proper gear selection would be

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[1] Slip is the relative movement in the direction of travel at the mutual contact surface of the traction device and the surface which supports it (ASAE Recommendation: ASAE R296.1).

[2] Traction device is a device for propelling a vehicle using the reaction forces from the supporting surface.

facilitated if a reliable and easy to use slip meter were made available for all tractors.

Conventional methods of slip monitoring are based on counting the number of drive-wheel revolutions required for the traction equipment to travel a given distance under no load and again under a steady load conditions. These methods are cumbersome and time consuming and do not provide the information about the instantaneous value of slip. Newer electrical slip meters developed at the University of Saskatchewan (Paulson and Zoerb, 1971; Paulson and Elliott, 1974) monitor the dynamic slip but require an additional wheel and are generally too complex to be considered as a practical aid to the traction equipment operator.

Microwave Doppler radar has been used for many years in navigation, traffic control and intruder detection applications. Its capabilities and limitations in these applications have been studied in great detail (Barlow, 1949; Skolnik, 1962). Its application as a speedometer, which has been reported recently (Hyltin, et al., 1973; Grimes and Jones, 1974), shows that it can be used to measure true ground speed of automobiles and other land vehicles regardless of the type of surface (or its condition) over which the vehicle traverses.

The objective of this research was to investigate and develop a slip monitor for traction equipment based on the microwave Doppler radar and to evaluate technical and economic feasibility of using the monitor on traction equipment in order to maximize tractive efficiency and limit tire wear from excessive slip. The concept of Doppler radar slip monitor (DRSM) is based on employing two Doppler radars to continuously sense the actual ground speed of traction devices and the circumferential velocity of the drive-wheel. The difference between these two velocities normalized to the circumferential velocity is the dynamic slip.

CHAPTER II

REVIEW OF LITERATURE

When a wheel or track moves a tractor, with or without an attached load, some slip of the traction member occurs. This phenomenon is usually referred to as travel reduction, and may be expected to increase with increasing load (*Tractors and Their Power Units*, 1963, Barger et al., p. 272).

Slip and Its Meaning in Traction Equipment

Slip (slippage) is the actual relative movement that occurs between the surface of the traction device and the surface of the soil (Vanden Berg, et al., 1961). Slip value is not uniform over the contact area and is less than the travel reduction value. The actual value of slip cannot be separated from the other sources of travel reduction and thus cannot be measured. The travel reduction is based on the actual distance travelled forward, and can be accurately determined. Two distinct phenomena related to travel reduction have been identified: firstly, the relative movement at the contact surfaces which in the case of a rubber tire includes flexing of rubber, deforming of soil, sliding of rubber surface on soil surface and twisting or bending of lugs, and secondly, the actual distance travelled forward. Zero travel reduction can be determined when the traction devices travel under zero conditions. A.S.A.E. Recommendation (ASAE R296.1) has described that zero conditions may be those of zero net traction, or zero torque for the traction device as well as zero drawbar pull for the vehicle. In this study, zero travel reduction was determined at zero drawbar pull (no load). Slip and travel reduction, however, are sometimes used synonymously, and are frequently expressed in percent.

A rolling traction device must slip in order to obtain a traction force for an adequate drawbar pull at some finite forward speed. In addition to being able to develop an adequate drawbar pull, the traction device must be able to develop enough speed so that an adequate amount of work can be accomplished. Gill and Vanden Berg (1967) have shown that slip and velocity are related and therefore slip is important in determining the forward speed of traction devices. Power efficiency which is proportional to forward speed and hence to slip of the traction device, is an important criterion when the device is operated for long periods of time. Thus, in order to obtain the maximum power efficiency, the device should be operated at some finite value of slip.

Review of Slip Monitoring Systems (Non-Radar)

Various studies have been made in an effort to control drive-wheel slip of agricultural traction devices below some arbitrary limit. Measurements of drive-wheel slip were made on 300 tractors at work in southern Ontario during the spring and fall of 1961 and 1962 (Southwell and Jackson, 1963). The readings obtained show that drive-wheel slip ranged from one percent to 36 percent, the average being 8.4 percent. These measurements indicate that travel reduction of greater than 15 percent is uncommon for some tillage operations. Similar tests were performed in various parts of Saskatchewan in 1964 on 30 tractors (Horne and Johnson, 1965). Draft and slip measurements were made under typical operating conditions during summerfallowing. A plot of slip versus percentage of tractors tested, showed a curve peak at about eight percent slip. Slip values ranged from 3.5 to 11.5 percent.

Traction tests performed at the University of Manitoba to determine the characteristics of different tractive devices on different field conditions have been reported by Friesen, Domier and Townsend (1969). It was shown that the maximum drawbar horsepower occurred when the slip was between 7 and 25 percent, depending on traction equipment, gear selection and field conditions. In most cases, slip at the maximum drawbar horsepower obtained was between 7 and 16 percent.

During the past twenty years, many technical papers have dealt with methods for the measurement of drive-wheel slip of agricultural tractors. Reznicek et al. (1957) mounted electrical resistance strain gauges on the rear tire tread bars. By measuring the bending strain of the tread bars of the tire and the comprehensive peripheral deformation of the tire when rolling on a firm surface, they obtained a relationship between tire slip and the force transmitted.

A method of measuring the slip of agricultural machines was also described by Boroshok (1956). A crank attached to the ground wheel of the machine under test operated a guide-mounted slider, which was fitted with a recording pen. The trace was made on a disc whose angular speed was synchronized with the forward movement of the machine. The disc was driven by friction from a piece of cord, one end of which was anchored to the ground. The cord was unwound as a result of the forward travel of the machine. The pen traced a symmetrical curve when no slip occurred, but when slip occurred, the traced curve became flattened as well as asymmetrical.

A special purpose analog computer for continuous slip calculations with an automatic initial balance for adjusting the initial slip value has been reported by Prather and Schafer (1968). Many experiments in slip measurement of traction devices were performed at a traction test site in the National Tillage Machinery Laboratory, Auburn, Alabama. Two linear DC generators, one coupled to the drive shaft of the tractor engine and the other to a free wheel mounted on the main carriage and rolling on the rail along the side of the test bin were used to provide DC voltages proportional to the angular velocity of the traction device and to the forward velocity of the main carriage respectively. The pull between the tire and the main carriage was also monitored to determine a desired value of the reciprocal of the rolling radius of the traction device. This variable was sensed by a strain-gauge force dynamometer. When zero pull was obtained, the computer automatically adjusted the initial balance (zero slip). After this initial balance was set, the angular velocity of the tire was increased and positive slip was then developed.

A system for direct indication of tractor-wheel slip was described by Zoerb and Popoff (1967). Two DC tachometers, one coupled to the power-take-off shaft and the other to a two-wheeled cart, provided analog voltages proportional to the average speed of the two drive wheels and to the actual ground speed. These two signals were supplied to a passive circuit consisting of resistors, capacitors, and a galvanometer. A single-turn potentiometer was then manually adjusted to achieve a null, while percent slip was read directly from a dial behind a pointer attached to the potentiometer shaft. Although the system provided a direct measurement of slip, it was extremely difficult for the tractor operator to manually adjust the potentiometer during the test run. The system was then modified (Zoerb, Paulson and Archibald, 1971). A DC servo system with tachometer signals as inputs was used in order to obtain automatic and continuous indications of the tractor-wheel slip. Experimental results of the field tests showed, however, that the values of slip measured by conventional means and the values indicated by the slip meter were not in good agreement for some runs. The error was believed to be due to the excessive electrical noise in the tachometer output signals.

The tractor-wheel slip indication system was again modified (Paulson and Zoerb, 1971). Magnetic pickups were used, in lieu of DC tachometers, to eliminate the problem of transducer noise. It was reported that the magnetic pick-up slip meter yielded relatively accurate results when the slip occurring was relatively constant. However, it was not able to instantly respond to a rapid change which could occur if one or both of the drive-wheels were to encounter a sudden change in surface conditions.

Recently, a digital slip meter developed at the University of Saskatchewan was reported by Paulson and Elliott (1974). Two magnetic pick-ups, one coupled to a fifth wheel assembly and the other to the power-take-off shaft, were employed to sense the ground speed and the average RPM of the tractor drive wheels. The outputs of the magnetic pick-ups were supplied to a digital system. The slip meter was calibrated when the tractor ran under no load and it provided a direct digital indication of tractor-wheel slip when the tractor ran under load in the same gear. This slip meter also yielded sufficiently accurate results compared with the results obtained from the conventional method.

Paulson (private communication, 1975) mentioned that monitoring tractor-wheel slip with the fifth wheel had some basic disadvantages. The fifth wheel yawed slightly instead of following exactly in the wheel track. Thus, it did not provide accurate results of the ground speed and being an additional attachment, made the instrument cumbersome and inconvenient for the tractor operators.

Doppler Radar Rough Surface Considerations

Among the major parameters affecting radar scattering from the ground, roughness of the surface is probably the most important factor since it determines the amplitude of the return signal and hence the signal to noise ratio (Skolnik, 1962). Surfaces are characterized by RMS values of surface roughness which for smooth surfaces is much smaller than the wavelength. Asphalt and concrete may usually be considered as smooth surfaces at frequencies higher than 10 GHz. Rough surfaces at these frequencies include grass-covered and plowed fields, where the RMS values of surface roughness are comparable with the wavelengths.

Berger (1957) has shown that the Doppler signal returned from a random rough surface has the frequency spectrum characterized by Gaussian distribution centered around the mean Doppler frequency. This characteristic was attributed to the summation of many return signals from small scatterers illuminated by the radar beam. In that analysis, however, the effect of statistical properties of random rough surfaces was neglected. In another paper (Broderick and Hayre, 1969) it was shown that neglecting these properties leads to an incorrect Doppler frequency spectrum. Broderick and Hayre took the statistical properties of a random rough surface into account and assumed the rough surface to be stationary and the radiating source to be moving with a certain velocity along a one-dimensional axis. The antenna beam width along the azimuth was assumed to be small. They have shown that the Doppler frequency spectrum is non-Gaussian for the case of a one-dimensional rough-surface model. They have also shown that the Doppler frequency sepectrum obtained is composed of three distinct components, one from the smooth surface and the other two from the rough surface. These frequency components produce a non-Gaussian frequency spectrum. Doppler return from a two-dimensional random rough surface was investigated by Sohel and Hayre (1972). They concluded that the Doppler frequency spectrum obtained was smoothed and peaked when viewed from angles far away from normal to the plane illuminated by the radar antenna. The spectrum was found nonsymmetrical around the nominal Doppler frequency. They also showed that the asymmetry and the width of the main lobe of the frequency spectrum increased with increasing roughness, whereas for decreasing roughness the main lobe became more rounded.

Much research has been done in the past on the measurement of back scattering properties of different surfaces. Grant and Yaplee (1957) measured the back scattering from water and several land terrains at wavelengths of 3.2 cm, 1.25 cm and 0.86 cm using vertical polarization. A two antenna zero intermediate frequency superheterodyne continuous wave Doppler system was used in this measurement. The system was calibrated and the ratio of the received power and transmitted power was measured. The values of average radar cross section of water and land echoes per unit area of the surface were calculated from this ratio and from constants of the system, and were plotted as a function of the angle of incidence. It was shown that the average radar cross section of water echo per unit area of the water surface is a complicated function of wind velocity or water surface condition and of the frequency of the incident radiation, but in general this value increases with frequency and wind velocity. It was also concluded that the back scattering of land is a function of the kind of terrain and of the frequency of the incident radiation, and under most conditions the value of the back scattered signal increases with frequency.

Cook and Waite (1972) measured the microwave reflectivity of sand and soil surfaces with varying moisture content and surface roughness in the frequency range from 4 to 26.5 GHz. Measurements were performed with a swept frequency bistatic reflectometer using both horizontal and vertical polarization. A network analyzer was used to record the transmit-receive power ratio as a continuous function of frequency. They showed that adding moisture to the soil roughens the surface due to cohesion of particles. They also found that the specular reflectivity of natural surfaces was reduced due to the effect of the discontinuous nature of the surface, both in structure and the distribution of moisture over the surface.

De Loor et al., (1974) studied the use of radar in classifying vegetations. The measuring radar system was installed on the stable platforms of a TV tower and was directed to the agricultural field where the radar back scatter coefficient was to be measured. It was shown that a single vegetation-type behaves as a Rayleigh scatter. They proved that the radar back scatter coefficient as a function of frequency and polarization is the only usable parameter to classify vegetation with the aid of radar.

Ulaby (1974) investigated the effect of soil moisture on the radar backscattering coefficient. He performed the experiments on two bare ground fields, namely, slightly rough and very rough and measured the spectral response in terms of the wavelength. A radar system mounted atop a 75-foot truck-mounted boom was used to measure the radar return at various frequency points across the 4 to 8 GHz band, at various incident angles, and for different polarization combinations. He concluded that the radar response to soil moisture content was highly dependent on the surface roughness, microwave frequency, and the angle of incidence.

Bush and Ulaby (1975) performed an experiment to determine the fading characteristics of backscattered radar signals from agricultural targets. A wide band 8 to 18 GHz radar system employing two antennae (transmit and receive) mounted atop a 26 meter hydraulically operated boom was used in this measurement. The targets included two different row crops (corn and soybeans), a continuous canopy (alfalfa) and bare ground. The mean value of scattering coefficient was plotted versus incidence angle for each of four targets. It was shown that corn and alfalfa yield higher scattering coefficient values than those obtained from soybeans and bare soil particularly at normal incidence angle.

Solid-State Devices in Microwave Doppler Radars

A survey made recently (Berson, 1976) has shown that four types of solid-state devices, namely transferred-electron (TE) devices, impatts, trapatts, and baritts are available for power generation at high radio frequencies as well as at microwave frequencies. TE devices are made of either gallium arsenide or indium phosphite and are called Gunn diodes when they operate in the Gunn or transit-time mode. Impatt diodes are fabricated from either silicon or gallium arsenide whereas trapatts and baritts are generally made from silicon. Berson has mentioned that TE devices, impatts and baritts are suitable for continuous-wave (CW) transmitter and self-mixing radar applications.

Among the above mentioned devices, TE devices (Gunn diodes in particular) are generally employed as microwave sources in CW Doppler radars used in automotive applications. The reasons in selecting Gunn diodes for these applications are low cost, excellent tunability and very wide range of operating frequencies as compared to impatts and baritts. In addition, they usually exhibit sufficient output power and efficiency at low operating voltages.

Solid-state devices are also used as nonlinear elements in microwave mixers and detectors. A recent review by Anand and Moroney (1971) has shown that three types of nonlinear devices, namely, germanium back diodes, silicon or gallium arsenide point-contact diodes, and Schottky barrier diodes are useful for these applications.

Because of having greater susceptibility to burnout, circuit complications, and fabrication difficulties than Schottky and point-contact diodes, back diodes have not found as wide acceptance as mixers and detectors at microwave frequencies. From these devices, the Schottky diode is the most suitable for Doppler radar applications since it exhibits the lowest overall noise figure, particularly at low frequencies. Its sensitivity is relatively high but lower than that of point-contact and back diodes at zero or very low bias.