Björn Bernhard and Volkmar Schlotter, Hohenheim

Tyre dynamics with water ballasting

The tyres of tractors and self-propelled harvesters have a sustainable effect on driving safety and comfort. In practice, tyres are often ballasted with water to increase wheel weighting which means that an alteration in their dynamic properties can be expected. In Hohenheim the vertical direction dynamic properties of tractor tyres were investigated with an increase in spring stiffness determined. Reduction of the cushioning air within the tyres also led to an enlarging of the natural frequency and thus to an increase in the critical speed.

Dipl.-Ing. sc. agr. Björn Bernhard and Dipl.-Ing. Volkmar Schlotter are members of the scientific staff at the Chair of Procedural Technology in Plant Production with Agricultural Engineering Basis at the Institute for Agricultural Engineering (director: Prof. Dr.-Ing. Dr. h.c. H.D. Kutzbach), University of Hohenheim, Garbenstraße 9, 70599 Stuttgart, e-mail: bernhard@uni-hohenheim.de

Keywords

Tyre dynamics, longitudinal spring and damping characteristics, water-filled tyres, resonance frequency

Literature details are available from the publishers under LT01102e or via Internet at http://www.landwirtschaftsverlag.com/landtech/local/fliteratur.htm

In practical farming operations tractor tyres are often ballasted with water to increase wheel loadings. This enables greater power transference. Advantages compared with ballasting with weights are less load on the axles and cost savings. But it can be expected that water ballasting changes tyre properties. Up until now the dynamics of tyres thus filled have been rarely investigated and are thus largely unknown.

Basics

The oscillation behaviour of tractor tyres in vertical and horizontal directions were investigated in replication and through models predictions made as to the expected springing and damping behaviour. Based on the investigations of [1 and 2] a non-linear tyre model was developed in Hohenheim.

To determine springing and damping behaviour in the vertical direction, the Voigt Kelvin model was applied:

$$F_R = F_C + F_D \quad (1)$$

The suspension force FC showed a non-linear behaviour which could be demonstrated through a potential function:

$$F_C = c_1 \cdot s^{c_2} \quad (2)$$

Applicable for the damping force F_D in association with the spring absorption velocity is:

$$F_D = d_V \cdot \dot{s} \quad (3)$$

Out of the data collected in the investigations it was possible to deduce the non-linear parameters C_1, C_2 and d_V.

Moving belt testing station

On the moving belt test station at the University of Hohenheim which was used for the trial (*fig. 1*) the tyres rolled on a 60 cm wide steel belt onto which was stuck sandpaper (40 graining) in order to simulate a roadway surface. The steel belt was driven by a direct current electric motor, the driving speed could be varied infinitely from 0 to 62 km/h.

A Teflon-surfaced steel plate was positioned under the contact point between tyre and steel belt under which three force-measurement contacts (1, 2 and 3) were positioned for measurement of the vertical wheel force F_V. The wheel itself was positioned in a fork which was attached in the upright position by two force-measuring bolts (4, 5). Through these, the horizontal forces F_L could be determined. To simulate higher wheel loadings, the fork was ballasted with steel weights. Additionally the belt speed (6), the wheel speed (7), the angle of rotation (8) and the rolling radius (9) of the wheel were determined.

Method

Three series of trials were carried out under variations of tyre pressure, wheel load, driving speed and amount of water ballast. With the ballast variations, the manufacturers' advice as to maximum ballasting was observed and wheel load adjusted accordingly so that the vertical forces in the surface contact areas remained constant. During the rolling trial, the tyre rolled at 1 km/h on the belt. In spring-damping trials the tyre was raised and dropped so that the free tyre damping effect could be observed on the moving belt. In the trials for resonance frequency the tyre was run through the speed spectrum. Resonance frequency and critical speed could be determined according to the variations in the vertical forces and rolling radius.

Results

The rolling trials served to determine the non-roundness of the tyre circumference. This had substantial negative influence on the driving behaviour, especially at higher speeds.

With increasing levels of water ballasting there occurred at first a decrease in the variations of the order first as well as those of the second from rolling radius and vertical

Table 1: Resonance frequencies depending on tyre load and filling level

Wheel load in kg	Resonance frequencies in Hz – Amount of water ballast: without	half	maximum
1000	2,46	2,70	2,65
1500	2,05	2,16	2,20
2000	1,52	1,92	1,93
2500	1,52	1,60	1,72

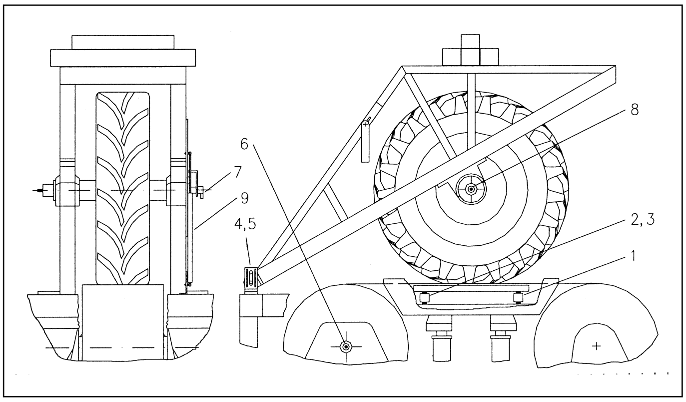

Fig. 1: Flat-belt tyre test stand

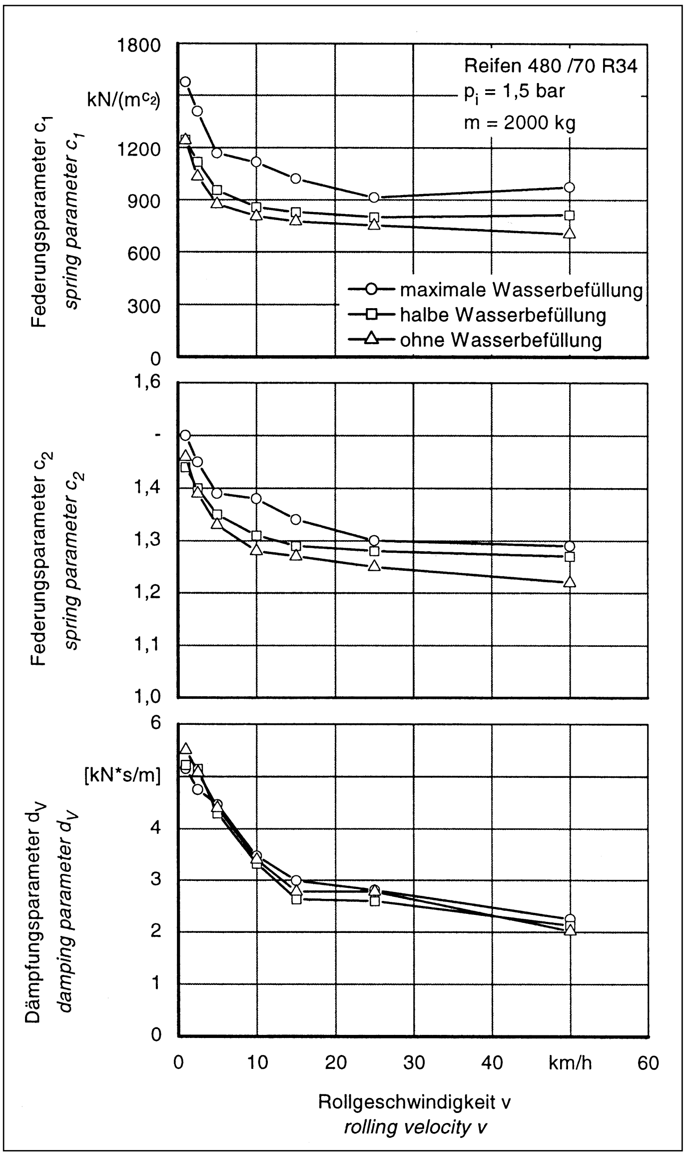

Fig. 2: Impact of the water ballast on the tyre parameters

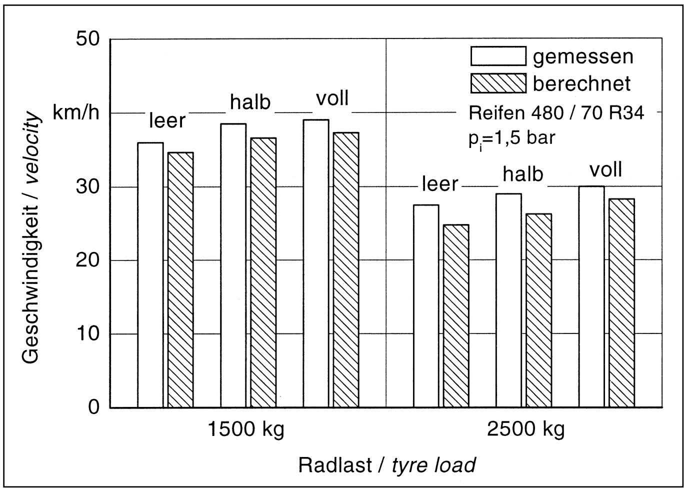

Fig. 3: Variation of the critical velocity for different filling levels

force. With constant wheel load the rolling radius increased in line with increased level of water ballast. Both of these effects could be explained through the inertia of the water compressed within the tyre.

The target of the spring-damping trial was the determination of C_1, C_2 and D_V. The spring-damping trials indicated a strong dependence of the spring and damping parameters on the velocity (*fig. 2*). The spring as well as the damping was reduced with increasing rolling velocity. All parameters fell strongly up to 15 km/h and were almost constant for higher speeds.

The reduction of spring stiffness and damping capacity for speeds up to 15 km/h can be explained through the behaviour of polymer materials. When speed is increased this behaviour leads to there being increasingly less time for creepage, and thus hardening, in the area of the tyre cover and running surface which have contact with the road. This influence of the velocity appears to be independent of wheel load and water ballasting. With very high rolling speeds this effect was overlaid by the influence of centrifugal force. The cover material is pressed outwards so that a larger total force of spring and damping stand against one another and this means that the spring and damping values remain constant for high speeds.

Whereas, no dependency was able to be determined between damping and amount of ballasting, the suspension is strongly associated with degree of ballasting. The clear hardening of the tyre can also be explained in this case through the mass of the pressurised water in the tyre. Additionally, the suspension-giving volume of air within a tyre is reduced in a water-ballasted tyre which leads to a further hardening.

With the help of a Fourier transformation the natural frequency of the tyre was measured for the resonance frequency trials (*table 1*). The increase was caused by the inconsistent roundness of the rolling tyre. In table 1 only the natural frequency of the first order are depicted, the oscillations of a higher order and the stollen (post) stimulation were ignored.

As a result, with increasing wheel load a reduction in the resonance frequency was shown. Filling the tyre with water increased the resonance frequency. If the natural frequency, f, and the current rolling radius, r, of the tyre is known, the critical velocity v_{krit} can be calculated:

$$v_{krit} = 2 \cdot \pi \cdot f \cdot r \qquad (4)$$

In *figure 3* the measured results for critical velocity, and those calculated according to equation 4, are shown. Both indicate a movement to higher critical velocities for water ballasting. Noticeable is that the calculated speeds lie around 1 to 3 km/h below those measured. In that the speed during the trial is continually increased, this difference can be attributed to the catching-up of the velocity.

Outlook

In order to increase the relevance for practical farming of the investigated results, further work should also be aimed at assessing the dynamic behaviour of water ballasted tyres in longitudinal and lateral directions. And because high rotational masses are involved in such cases there's also a need to investigate dynamic loads on the axle with water ballasting and also the power requirements for acceleration and braking.