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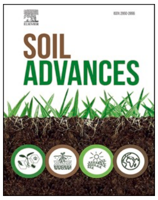

Acoustic monitoring of soil water content during tillage and sowing

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ABSTRACT

Climate change has had an impact on soil cultivation and sowing methods, as precipitation levels and dry periods have changed. In addition, agricultural areas have become considerably larger on average in recent years due to numerous farm closures, particularly in Europe, and a simultaneous increase in the area per farm. This has increased the inhomogeneity of arable land in terms of water absorption and retention capacity. Against this background, the need for real-time monitoring of soil moisture, particularly during cultivation, is more important than ever. Existing methods are not suitable for this purpose as they are costly and do not have the resolution to monitor site-specific soil moisture. This study aims to test the possibility of measuring changes of soil moisture using vibro-acoustic sensors during soil cultivation. The advantage of measuring the soil water content via the vibration of the cultivator coulters is that this indirect method allows the sensors to be implemented on the tillage machine, thus enabling spatial and continuous in-process control instead of just a point recording of the soil water content. Specifically, this study investigated the possibility to monitor soil water content by measuring the vibration acceleration on a cultivator share. The results showed that sensors at different positions of the device had equally meaningful signals. Additionally, the R^2 value of the linear regression ranged from 0.645, with a root mean square value up to 0.933 % volume. Overall this study highlights the feasibility to monitor soil water content by using vibroacoustic sensors, more specifically piezoelectric accelerometers, during soil field operations such as tillage and sowing.

1. Introduction

Soil moisture is crucial for plant growth, crop water requirements and irrigation planning (Sharma and Kumar, 2023). Soil moisture also determines the timing, type and method of tillage and sowing depth, to name but a few. In addition to the required tensile forces, the trafficability of the soil and the resulting compaction significantly influence the achievable tillage result. Information on soil moisture in conjunction with the soil type, therefore determines the optimum time and method of tillage. (e.g. Kalinin et al., 2020; Guan et al., 2015; Romaneckas et al., 2022; Walia et al., 2024)

If the soil moisture needs to be considered for specific areas during cultivation, it is insufficient to have a single value for the entire field. Each area must be checked before cultivation and moisture levels assessed, for instance, using a moisture meter. Such a measurement is very time- and energy-intensive. Furthermore, the actual soil moisture can deviate between measurement and cultivation due to evaporation. Determining the soil moisture during cultivation would therefore be a great advantage.

Due to the structural change in agriculture in recent decades, particularly in Europe, many small areas have been merged and cultivated as one arable area to enable a more efficient cultivation (Mehrabi, 2023, Hemmerling et al., 2014). As a result, the soil conditions on a field can vary significantly. On the other hand, using advanced farming systems is becoming increasingly sensible and necessary to manage resources efficiently and effectively. Such methods are already established in crop production in particular, for example in the application of synthetic fertilizers and plant protection measures. There are already promising field studies in soil cultivation and sowing, e.g. with a horizontal penetrometer (Zeng et al., 2008, Sun et al., 2006). However, there is still a lack of appropriate, robust real-time measurement methods available to users with a high measurement or averaging rate that enable

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statements to be made about the current, site-specific soil conditions. This includes, above all, the on-the-go determination of soil moisture. In addition to optimizing soil cultivation, the advantage is to achieve precise sowing depth, in particular, for faster crop establishment and homogeneous crop growth. The expected outcomes include decreased weed pressure, lowered erosion risk and enhanced process reliability in direct sowing. Furthermore, on dry sites where water availability for sowing is limited, the need for energy-intensive and costly additional watering could be dispensed through moisture-dependent seed placement. Moreover, moisture-dependent sowing can be expected to increase yields due to more uniform crop development (Knappenberger et al., 2005).

A relative assessment of moisture levels across different parts of a field would be insightful. The farmer could adjust the tillage machine at the start of tillage or sowing in a field according to good agricultural practice by visual and haptic control and, if necessary, record the soil water content with a sensor. The vibration values determined during this adjustment phase then serve as a reference for the cultivation of the entire field.

The aim of this study was to investigate the correlation between soil water content determined by a soil moisture meter and vibrations mounted on a soil tillage implement. Specifically, the aim was to find whether changes in soil moisture affect the vibration acceleration on the cultivator shares. Furthermore, the investigation aimed to determine the feasibility of vibro-acoustic monitoring of soil moisture using accelerometers on the shares of soil tillage implement. In addition, the research study aimed to clarify whether sensors at different positions of the cultivator yield comparable or significantly different measurement results.

2. State of the art of soil moisture measurement

The adequate and environmental management of arable land requires precise knowledge of soil moisture, whether current, site-specific, or sub-area-specific. In general, there are various methods for determining moisture, which are divided into direct and indirect measurement methods. Direct methods involve taking soil samples, followed by drying, extraction or chemical reactions for subsequent measurement. In contrast, indirect methods are based on physical and physicochemical properties of the soil that correlate with the moisture content (Stacheder, 1996). Common methods include tensiometric, gypsum block-based and time-domain or frequency-domain reflectometric approaches. These techniques differ not only in their physical principles, but also in their handling, complexity, costs and measurement accuracy. The analysis is usually carried out in the laboratory or stationary in the field, which entails time and area-specific restrictions.

2.1. *Soil moisture modeling*

The limitations of applying these methods in agricultural practice can be addressed by providing real-time area-wide soil moisture data based on modeling (BLE, 2021). Soil moisture measurements are carried out to develop the simulation methods. This means that soil moisture is measured manually or automatically using permanently installed measuring probes on individual areas that vary from region to region and from different soil types. This data is then used to integrate the measurement across the entire area. With knowledge of the measured values in different regions and different soil types, soil moisture is then modeled/predicted nationwide using a simulation model. In addition, an optical measuring system is to be developed that can measure soil moisture without contact while the tractor is driving over it.

Despite these efforts, the fact that soil conditions can vary considerably within a field is not taken into account.

2.2. *Sub-area specific offline determination of soil moisture*

While such control is already standard for nitrogen fertilization, determining soil moisture in management area is time-consuming with potential deviations caused by evaporation between measurement and cultivation. A few methods that could in principle be considered for this task are briefly mentioned here.

When using an infrared sensor (IR sensor) to measure soil moisture, it characterizes the distinct reflection behaviour of moist soil compared to dry soil. The IR method works with a transmitter-receiver combination. In detail, it emits light radiation of a certain wavelength, and the reflection is captured by a special IR diode. Even if the actual measuring process is carried out at high speed, it is problematic for the field-related application, as each substrate must be calibrated in order to make reliable statements regarding soil moisture (Henle, 2002). As a result, this method is not suitable as a basis for site-specific measurements due to the excessive measuring effort and cumbersome calibration.

Jantschke et al. (2005) used the radiometric method for determining soil moisture in stop-and-go-operation. Their method was based on measuring the count rate of neutrons previously emitted from a radioactive source and introduced into the soil. The intensity of the remaining, uncollided neutrons can be measured with a BF3 detector (proportional counter tube) and related to the volumetric soil water content. Due to the fact that the neutron radiation is also slowed down by crystalline water and organic substances in addition to free water, it is difficult to make a clear statement about the soil water content with this system without further dependencies (Melchior, 1993; Bohleber, 1993).

The most commonly adapted and used technique for mapping soil moisture is the measurement of electrical conductivity. The measurement is dependent on factors such as ionic strength, soil temperature and texture (Lück et al., 2000) and also includes an unclearly defined soil volume, so that this method offers more the possibility of an overview than an exact, point-precise measured value. Therefore, the system is only partially suitable for implementing a site-specific or dynamic measurement of soil moisture (Jantschke et al., 2005).

2.3. *Sub-area specific online determination of soil moisture*

Time Domain Reflectometry (TDR) is presented by Jantschke et al. (2005) as a method that, in principle, can be used for the dynamic determination of soil moisture. In this method, the propagation time of an electromagnetic wave in the soil is measured. There is a direct correlation between propagation time and soil moisture, which is largely independent of conductivity (Stacheder, 1996). The determination of the current soil moisture depends on texture, soil type and pore size. When measuring soil moisture with a TDR sensor, good soil contact must always be ensured to obtain unbiased measurement results. The geometry and design of the sensor enable the measurement of a precise, relevant soil volume. The TDR technology has decisive advantages for the dynamic measurement of soil moisture, such as the precisely measured relevant topsoil volume and, above all, the independence of calibrations before each measurement. This method therefore appears to be suitable in principle for the development of a mobile measuring system.

Jantschke et al. (2005) and Jantschke et al. (2006) investigated the TRIME method based on the TDR method. The TRIME method acts as a high-precision stopwatch with a resolution of around 10 ps by measuring the time until the reflected TDR signal exceeds an adjustable voltage level. In the tests, a measurement accuracy of around ± 5 % was determined, which would be more than sufficient for controlling soil cultivation or sowing technology. The tests showed a significant correlation of the data obtained to be able to predict the water status of the field after defined precipitation or irrigation events. A major limiting factor of the system is the penetration depth of the dynamic TDR detection. The prediction model has to deal with a soil layer close to the surface (Jantschke et al., 2006). The authors conclude that initial concepts of prototypes for manual measurements in stop-and-go operation in the field using GPS data for mapping have been successfully tested. Further development of the fully mobile and dynamic probes will enable continuous measurement of soil moisture during operation. For this purpose, suitable devices for dynamic soil moisture measurement are to be designed and tested, which are able to carry out any number of measurements within the field crossing at normal working speed and thus carry out soil moisture measurements in the relevant volume of the topsoil. The authors also point out that there is a need for research on the probes with regard to sensor-soil contact during measurements and crossing the field (Jantschke et al., 2006).

However, Sun et al. (2006) and Huang et al. (2017) impressively demonstrate the possibilities of mobile soil moisture measurement by measuring electromagnetic conductivity with different setups and under different boundary conditions and demonstrate their successful use in field tests.

2.4. *Acoustic-based determination of soil moisture*

The need to measure the moisture of agricultural soils with an accurate method in situ and in real time was focussed on by Adamo et al. (2004). They estimated moisture using a mathematical model by measuring the speed of sound in the medium, establishing an accurate relationship between the two quantities, based on the work of Brutsaert and Luthin (1964). The authors derived the velocity-moisture curves, the conditions for the actual validity of the curves and the appropriate sonic frequency for performing the measurement for a wide range of agricultural soils in different physical conditions in the model.

A promising approach to indirectly estimating soil moisture via a, possibly mobile, real-time determination of soil porosity is presented in Bradley et al. (2024). The method is based on simultaneous, multiple angle measurements of ultrasonic reflections from the soil with a sampling frequency of 25 kHz. The method is non-contact and typically from sensors mounted on a small farm vehicle around 1 m above the soil surface.Meisami-Asl et al. (2013) investigated the measurement of moisture content in soil using an easy-to-use acoustic wave system on-site and in real-time. The system consists of the propagation of acoustic waves, such as swept-frequency sound waves (10–300 Hz) and multi-tone sound waves (120 Hz), through the soil. Some characteristics of these acoustic waves allow an estimation of the soil water content. Suravi et al. (2019) confirmed that different moisture contents lead to variations in the acoustic properties of sand. Gorthi et al. (2020) investigated the change in sound velocity of soils as a function of moisture to develop a manual meter for rapid determination of soil moisture.

Xu et al. (2021) have investigated the use of the pulsed acoustic wave (PAW) method to measure acoustic soil parameters (SAPA). Acoustic parameters (acoustic pulse velocity and acoustic attenuation coefficient) were recorded from paddy soils (clay), red soils (loam) and lateritic red soils (clay loam) at different water contents. The experimental results of the field study confirmed the potential value of acoustic pulse velocity in the detection of soil volumetric water content. Based on the work mentioned here and a number of others, e.g. Sharma and Gupta (2010), Flammer et al. (2001) and Michael et al. (2002), it has been confirmed many times that the soil moisture content has an influence on the acoustic behaviour of the soil and that measurement in the field is possible with the appropriate technology. It is therefore obvious to consider acoustics as an indirect method of measuring soil water content. However, so far, no work has been known on how this principle has been investigated in combination with tillage and sowing as a system integrated into the machine for online determination of soil moisture.

An important area of application for acoustic sensors is the condition monitoring of machines such as bearing control. A deviation in the vibrations usually indicates a fault in the machine. Wearing parts can be monitored with these sensors and replaced in good time. This enables better utilisation of wear parts, as they do not have to be replaced prematurely for safety reasons (Kolerus and Wassermann, 2011). In the agricultural environment, the work on real-time detection of knife sharpness in forage harvesters using acoustic sensors mounted on the counter blade demonstrates the great potential of this technology. In particular, it should be noted that the parameters of the harvested crop, similar to the soil conditions during tillage, are, of course, not homogeneous but are subject to major site- and sub-area-specific dependencies and, above all, vary depending on the weather and the day (Siebald, 2017, Siebald et al., 2017).

Acoustic sensors can also be used to monitor nozzles. For example, a sensor attached to the outside of a milk tank can monitor the automatic cleaning process. This eliminates the need for a supervisor to monitor the process. It is also possible to use acoustic sensors to monitor the nozzles of a spray boom of a crop protection sprayer for a uniform flow rate. Optical sensors are often prone to errors in changing light conditions, so acoustic sensors are a reliable alternative (Wessels, 2014, Siebald et al., 2020).

3. Materials and methods

The study was carried out on the experimental site for irrigation and solar technology at the University of Kassel in Witzenhausen, Germany. On average, the area of the test site consists of loamy sand soil texture with 10–13 % soluble / drainable components (fraction < 0.01 mm) from young fluvatile sediment in an optimal state of development, according to Amelung et al. (2018).

3.1. *Measurement equipment*

A volumetric soil moisture sensor (ML 3 ThetaProbe Soil Moisture Sensor, DeltaT Devices, United Kingdom), three acceleration sensors and a pulse signal unit were used in the investigations. The pulse signal unit was used to synchronize the measured values of the soil water content with the measurements of the vibration acceleration sensors. Table 1 shows the sensors used in this research work, including the sensor type, the sensitivity, the measuring position on the cultivator and the designation corresponding to the measuring channels on the measuring device.

A three-row cultivator with nine staggered wing shares and a rear roller was equipped with the above-mentioned structure-borne sound sensors on two tool holders. Fig. 1 shows the three-row cultivator with a rear roller used in the research work.

The piezoelectric accelerometers were affixed to the middle (sensor positions 1 and 2) and left-side (sensor position 3) of the cultivator tines in the first row above the tine bolting in the travel direction. Fig. 2 shows the measuring positions of the accelerometers.

The pulse signal transmitter was used to synchronize the volumetric soil moisture measurement values and the sensor signals. When the button in the pulse signal transmitter is pressed, a pulse signal is immediately sent to channel 2 of the measuring system, thus providing an exact assignment in the acceleration time signals. Fig. 3 shows the position and mounting of the 4-channel measuring system NI USB - 4431 from the manufacturer National Instruments (left), which is used for data acquisition and processing, as well as the laptop used to control the system.

For each acceleration sensor (acc 0, acc 1 and acc 3) a total of 17

Table 1
Sensors: type or designation, sensitivity, measuring position, designation used in this study.

Type	Sensitivity	Measuring position	Designation
PCB 352C33	101.5 mV/g	position 0	acc 0
PCB 353B33	99.9 mV/g	position 1	acc 1
Acida 101.51–6–1	100.8 mV/g	position 3	acc 3

Fig. 1. Three-row measuring cultivator.

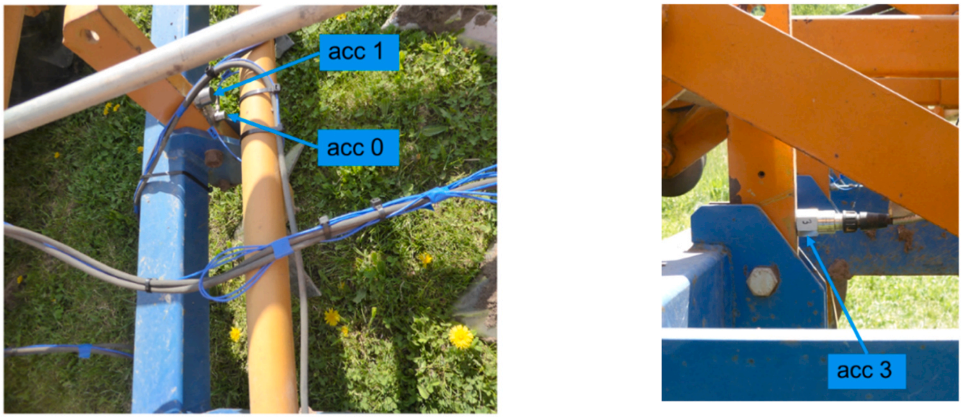

Fig. 2. Sensor positions 1 and 2 (left), sensor position 3 (right).

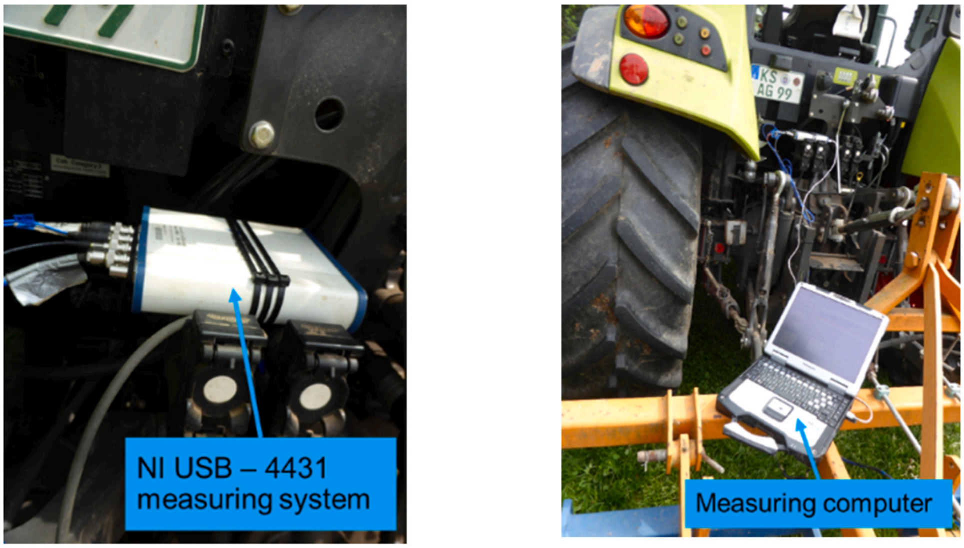

Fig. 3. 4-channel-measuring system NI USB-4431 (left) and measuring computer (right).

vibro-acoustic measurements were carried out on the cultivator. Before each measurement run, an average of 23 soil moisture values was determined all at a distance of 4 m on a row of 100 m. For each of these 23 soil moisture values, a structure-borne sound signal was measured using accelerometers. Thus 391 pairs of measurements (17 ×23) result in between soil water content and acceleration vibration for each sensor acc 0, acc 1 and acc 3 that means in total 1173 pairs of measurements have been determined.

3.2. Field experiments

In this research study, the volumetric soil water content was determined using a soil moisture sensor (ML 3 ThetaProbe Soil Moisture Sensor) that measures the specific volume of soil, which corresponds to the amount of water in the soil that could evaporate within 24 hours in a heating oven at a temperature of 105 °C (Metergroup, 2023; Meteotest, 2016).

The soil water content was measured volumetrically with a soil moisture sensor and the vibration acceleration with three acceleration sensors over a total length of 100 m at intervals of 4 m on a section of the test site during cultivating at two distances *a* and *b* defined by the measuring rod perpendicular to the direction of travel.

Fig. 4 schematically shows the first row of shares of the cultivator in the direction of travel with three shares, base frame and tines as well as the accelerometers attached to the tines. To measure the soil water content, a 10 cm deep hole was dug at positions *a* and *b* on each measuring rod and the value of the soil water content was measured volumetrically. It should be noted that the measuring needles of the soil moisture sensor measure over the entire length of the measuring needle from 0 to 6 cm. This means that the soil water content values determined with the soil moisture sensor corresponded to an average soil measuring depth of 13 cm. It was therefore necessary to ensure that the trench was dug at a depth of 13 cm in order to assign the soil water content to the vibration acceleration. This pulse then marked the position of the soil moisture measurement.

A deeper understanding of this synchronization was gained from the development of the vibro-acoustic time windows and the time window signals. When the cultivator was pulled through the soil by the tractor at a constant test speed of 3 km/h, the position of the soil moisture measurement in the acoustic signal was always marked manually in the experiments via the pulse signal transmitter when the measuring rod was reached, which was easily recognizable when the measuring rod was at the same height as the base frame of the cultivator (Fig. 5, left), by the rising pulse edge of the pulse signal (Fig. 5, right). An automatic detection of the measuring rod with a light barrier would also be conceivable and more practicable here, which could be implemented in the test setup in subsequent experiments. The position of the rising pulse edge in the experiment was referred to as the TimeMarker (TMi) position (with i = 1–23 = number of the time window) and corresponded to the end of the time window.

The start of the time window resulted from the consideration that the actual start of the measurement took place 164 ms before the marked position TMi at a tractor speed of 3 km/h and exactly when the cultivator tip was at the height of the measuring rod. The resulting time window corresponded to the time interval from TMi - 0.164 s to TMi and the distance that the cultivator coulter travelled from the tip to (approximately.) halfway. The distance between the two measuring rods was 4 m. The same procedure was used for each measuring rod, the end of the time window was marked with the pulse generator and the corresponding window in the acoustic time signal was calculated from this. This resulted in a total of 25 time window signals with a length of 164 ms for the entire measuring distance of 100 m. However, in practice, 23 acoustic time windows could be effectively calculated over the test period, as on average 23 soil moisture measurements were available over the entire test period on a measurement series of 100 m, due to the influence of the weather.

The diagram (Fig. 5, right) shows an example of the principle of acoustic time windowing in the measurement signal. The measurement signal recorded by the acceleration sensors during cultivating is shown in dark blue. The pulse signal fed into the external pulse channel (in black) provides the end of the time window in the measurement signal via the left pulse edge of the pulse signal and thus corresponds to the position of the TMi in the measurement signal. The length of the time window TW corresponds to the interval between TMi - 0.164 s and TMi and is shown in turquoise (Fig. 5, right). The positions of the soil moisture measurement values in the acoustic signal can therefore be recognized from the time windows (in turquoise).

3.3. Experimental evaluation

The measurement results for vibro-acoustic monitoring of the soil water content were methodically analysed in the time and frequency domain. The time signals in the entire measured frequency range (without filtering) were used for the analysis. The analysis was carried out using the imc FAMOS Professional 7.0 and imc FAMOS Enterprise 2022 (Fast Analysis and Monitoring of Signals) analyse software. To do this, the raw measurement data recorded with the 4-channel USB NI measurement system from National Instruments (NI) using the Signal Express software and available in TDMS format first had to be converted into the imc FAMOS format using an import filter.

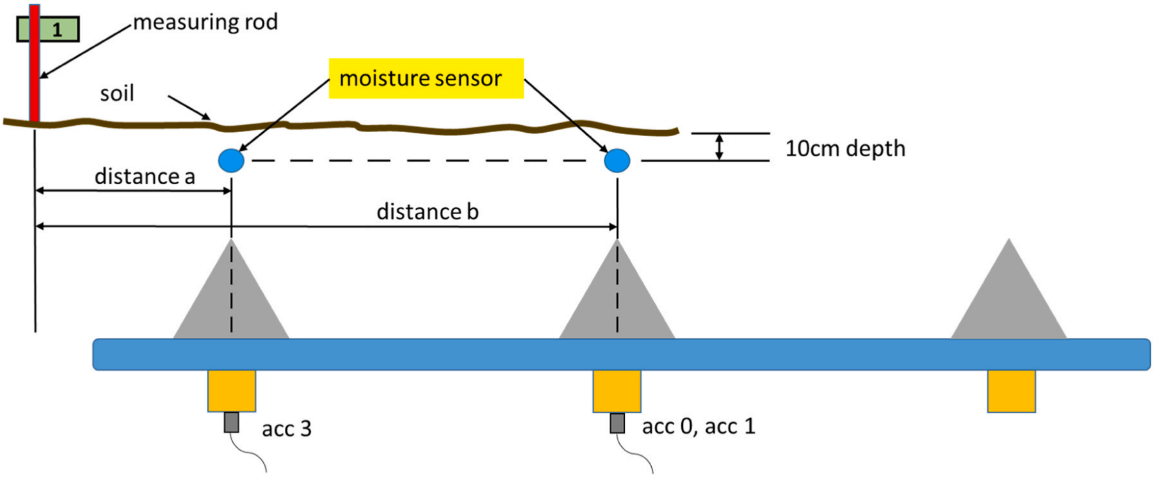

Fig. 4. Measuring rod, measuring positions of the soil moisture sensor, cultivator base frame with the shares, tines and measuring positions of the acc 0, acc 1 and acc 3 acceleration sensors.

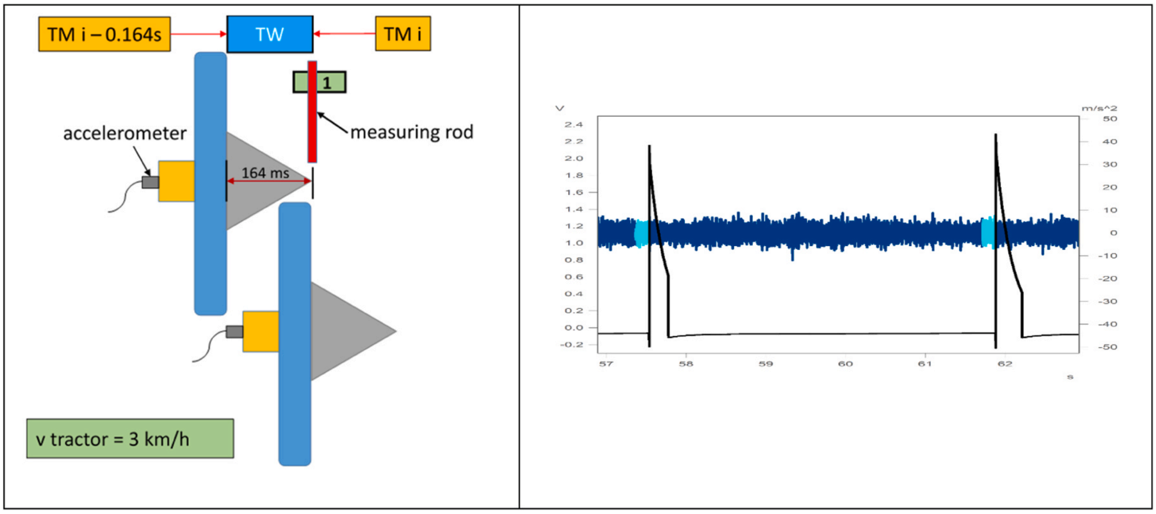

Fig. 5. Creation of the time window with a length of 164 ms (left) and time window signals (right).

The transformed temporal raw measurement data was then superimposed with the data from the pulse signal generator in order to determine the vibro-acoustic time windows (164 ms) over the course of which the soil water content was assumed to be constant during the tests. For each of these time windows, the RMS (root mean square) value and the maximum of the time window were determined as acoustic time characteristics in the time domain for each sensor acc0, acc1 and acc3.

For the analysis in the frequency domain, the corresponding frequency signals were calculated numerically from the time window signals using the Fast Fourier Transform (FFT). The Fourier transformation was performed using the function AmpSpectrumRMS_1 with the following function parameters: time window signals as input data with a sampling frequency of 51 kHz, width of the time window 8192 points, window type Hann window, 0 % overlap of the time windows, linear

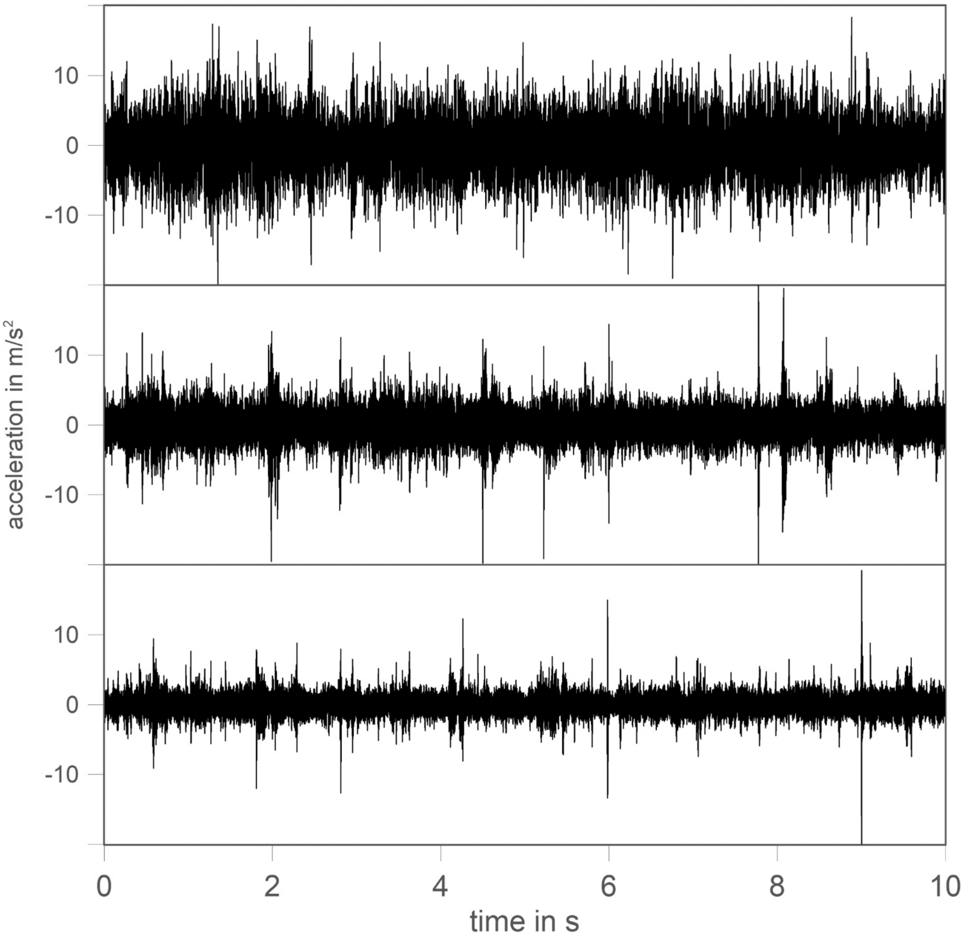

Fig. 6. Time signals of the acceleration (over 10 s measurement run) at sensor ai0, for different soil moisture (SWC): low SWC - top; medium SWC - middle and high SWC - bottom.

arithmetic averaging of the magnitude spectra. The mean value was determined over all calculated spectra, which are formed from a sliding Hann window.

The vibro-acoustic time and frequency characteristics calculated with imc FAMOS for each individual measurement day and for each acceleration sensor per soil moisture measurement value were then imported into Excel for descriptive statistical analysis. Of these vibro-acoustic characteristics, the RMS values of the signals of a measurement time window or a few consecutive time windows were considered for different measurement days and thus different soil moisture values. These results were visualized in point (XY) diagrams via the regression line and the R^2 value of the linear regression equation, whereby the mean of the temporal or spectral characteristic of the time window signals in m/s^2 was plotted on the y-axis and the mean of the soil water content in % by volume was plotted on the x-axis.

In addition, 3D amplitude spectra were calculated over time, which describe a 10-second section of a measurement signal of a low, medium and high soil water content, whereby each individual averaged amplitude spectrum appears one after the other as a segment of the data set in the 3D representation.

4. Results and discussion

The results are presented below with regard to various aspects to be investigated: Relative and absolute soil moisture in the time and frequency domain, differences regarding the sensor positions, comparison of the values for first and second pass and the comparison of different soil moisture ranges.

4.1. *Acoustic detection of relative soil moisture - time domain analysis*

As shown in the Materials and Methods section, the measurement signals were divided into a corresponding number of measurement windows according to the local assignment to the measurement points. Fig. 6 shows a comparison of the signals of the sensor ai0 for a 10 s section for different soil water contents or soil moisture values (SWC), low SWC (approx. 12.5 vol%) - top; medium SWC (approx. 20.8 vol%) - middle and high SWC (26.2 vol%) - bottom. It can be seen that the signal of the measurement has the highest average amplitudes at the lowest soil water content. The signal recorded at medium soil water content can also be sorted in the middle with regard to the vibration amplitudes and that the lowest vibration amplitudes were measured on average at the lowest soil water content. This is confirmed by the determination of the RMS values.

At a value of 3.23 m/s^2, the RMS value of the signal at low soil moisture is almost two times higher than at medium soil moisture (1.80 m/s^2) and a factor of three higher than at low soil moisture (1.06 m/s^2). On the one hand, the moist soil has a sound-damping effect by itself, and increased damping can also be expected due to the good fit between the soil and the tillage tool. In addition, the raised soil particles, which are generally smaller and softer, generate lower impulse forces in contact with the tool and consequently a reduced structure-borne noise input into the soil tillage implement. Furthermore, it can be assumed that the observed vibration behavior is due to the fact that as the soil becomes drier, the forces for working or breaking up the soil increase accordingly, and thus also the input of dynamic forces into the soil tillage tool or implement.

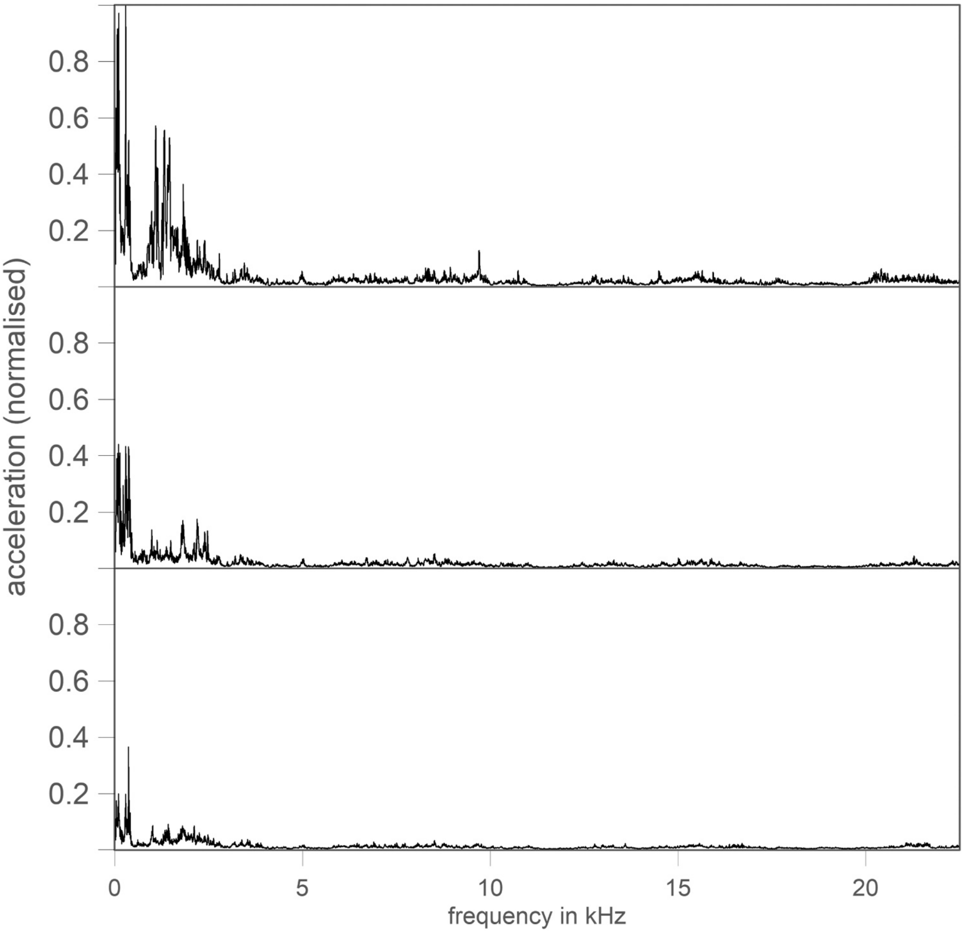

Fig. 7. Spectrum (up to 22.5 kHz) of the acceleration signal (over 10 s measurement run) at sensor ai0, for different soil moisture (SWC): low SWC - top; medium SWC - middle and high SWC - bottom.

4.2. Acoustic detection of relative soil moisture - frequency range analysis

A corresponding spectral representation of the measurement data for the different soil moisture levels (low, medium, high) can be seen in Fig. 7. For better comparability, the spectra were uniformly normalized. The maximum amplitude at medium soil moisture is approx. 44 % and at high soil moisture approx. 37 % of the value of the maximum amplitude at low soil moisture. It can be seen that the spectra are dominated by some striking resonance ranges. The maximum amplitudes are significantly higher in the range up to approximately 3 kHz than in the frequency range above. For this reason, the spectra in the range up to 3 kHz are shown in Fig. 8. Resonances at approx. 60–100 Hz; 280–350 Hz and 1.0–1.4 kHz can be clearly recognized here. It can be assumed that these are natural bending frequencies of the tool holder oriented in different spatial directions and different frequency orders.

To illustrate the temporal behavior, the 3D spectrograms for the measurement at low soil moisture (left) and comparatively at high soil moisture (right) are shown in Fig. 9. Since the acceleration amplitudes vary greatly in the different frequency ranges, the range up to 1.0 kHz is shown in the upper graphs, the range from 1.0 to 3.0 kHz in the middle and the range above 3.0 kHz at the bottom for better comparability. In all three frequency ranges, it can be seen that the vibration intensity is considerably lower at higher soil moisture levels. In addition, the resonances mentioned above in the frequency range up to 3 kHz, which in principle can be recognized in the 3D spectrogram by consistently higher amplitudes over time, are clearly visible. Above 3 kHz, some less prominent resonances occur in the range of 5.0–10 kHz. A resonance at 15 kHz and one at 20 kHz are also clearly visible.

4.3. Comparison of the sensor positions

The measurement obtained under medium soil moisture was used to compare the signals at the different sensor positions. Fig. 10 shows the corresponding spectra (up to 26 kHz) of the signals at sensor ai0 - top, ai1 - middle and ai3 - bottom. It can be seen that the occurring resonance ranges and thus the characteristic amplitude curve at sensor ai0 and ai1 are very comparable. The spectrum of the signal at sensor ai3, which was installed on a different tool holder than the other two sensors, shows a different curve. This could be a further indication that the resonances of the tool holder are responsible for the behavior below 3 kHz. In particular, the statement that the amplitudes in the frequency range up to approx. 3 kHz dominate the spectrum is confirmed for all sensors.

For a better comparison, the data up to 3 kHz can be seen in the Fig. 11. Here it can also be concluded that the detection of vibrations in the comparatively lower frequency range is less influenced by the exact position on a tillage tool holder than by the design of the holder. If the higher frequency range is considered, the vibration responses are no longer comparable, even at different positions on the same tillage implement holder, but are different. This is consistent with the fact that as the resonance frequency increases, the corresponding wavelengths decrease linearly and the amplitude sensitivity to the exact measuring point increases accordingly.

4.4. Acoustic based monitoring of absolute soil moisture - time domain analysis

Fig. 12 shows the mean RMS value of the acceleration signal at sensor ai0 for one-time window for all soil measured moisture values

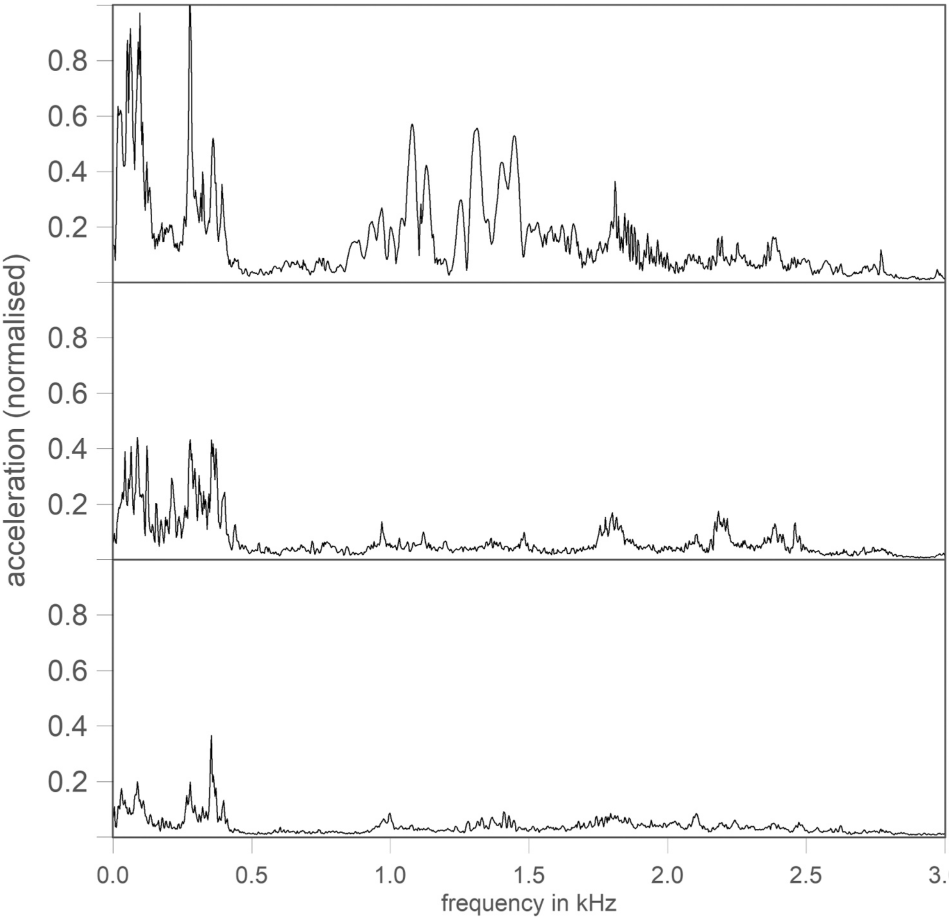

Fig. 8. Spectrum (up to 3 kHz) of the acceleration signal (over 10 s measurement run) at sensor ai0, for different soil moisture (SWC): low SWC - top; medium SWC - middle and high SWC - bottom.

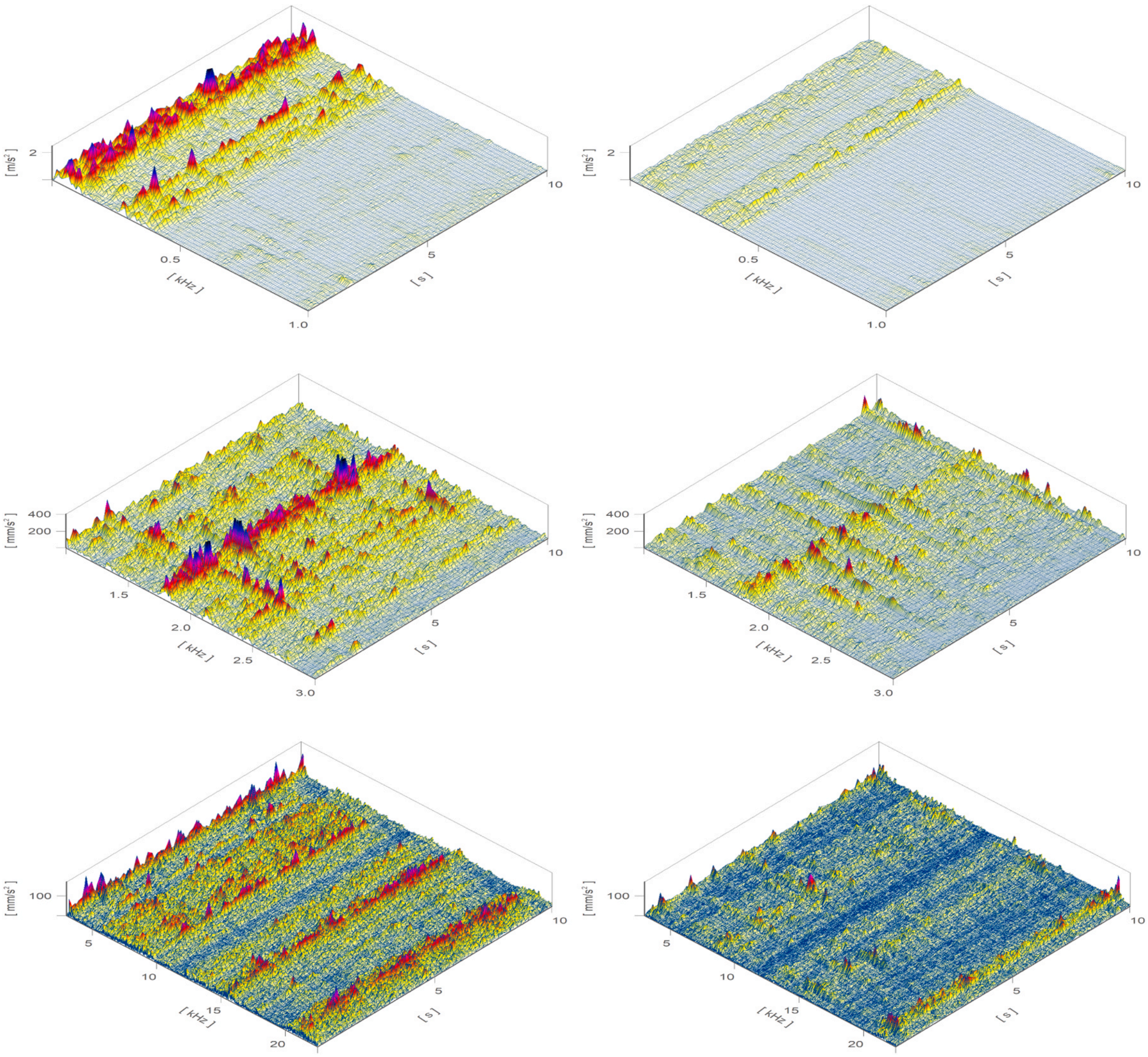

Fig. 9. 3D spectrogram of the acceleration signal at sensor ai0, low soil moisture (left) and high soil moisture (right). Frequency range up to 1 kHz (top), 1–3 kHz (center) and 3–22.5 kHz (bottom).

and for both crossings also. The linear regression shows an R^2 value of 0.642. The clustering of the data into a range of lower soil moisture and a range of medium or higher soil moisture can be observed, although this may be due to the test conditions, i.e. the soil moisture present on the various measurement days. The standard deviation for the low soil moisture range is 0.657 m/s^2, for the medium SWC range 0.541 m/s^2 and for the upper range 0.366 m/s^2.

4.5. *Comparison of the measurement data for the first and second crossing*

Figs. 13 and 14 show the mean RMS value of the acceleration signal at sensor ai0 for one-time window each for all soil moisture values investigated and for the first and second pass respectively. It is evident that the linear regression changes the values in both parameters (straight line slope and y-axis intercept), which indicates that the first and second pass are acoustically different. It is therefore also understandable that separating the two crossings results in higher R^2 values than when the crossings are considered together. These are 0.726 for the first pass and 0.749 for the second pass.

For the second pass the standard deviation of 0.35 m/s^2 is even lower than for the first pass at 0.46 m/s^2. On the second pass, the soil is already more homogeneous in terms of soil particles than on the first pass, so that the values on different sections, especially those that are closer together, have also become more comparable. This means that acoustically measurable parameters or boundary conditions that cannot be attributed to soil moisture are less significant.

4.6. *Comparison of data for different moisture levels*

Finally, as shown in Fig. 15, moisture levels were considered. For this purpose, the data from the second pass was sorted according to ascending moisture levels and three consecutive measured values were combined to form a level. This achieves a somewhat coarser resolution than when looking at each individual measured value, but a much finer resolution than when looking at the dry, medium and very moist areas. The mean value and the corresponding standard deviation were calculated for these three measured values. This results in an R^2 value of 0.933 in the linear regression. For the standard deviation, predominantly with values less than 0.5 m/s^2, the values for higher soil moisture values also tend to be lower than for low soil moisture.

5. Summary and outlook

The appropriate and environmentally sound management of arable land requires precise knowledge of soil moisture, both current and site- or sub-area-specific. There is a need for a real-time measurement method to determine the soil water content during or directly before soil

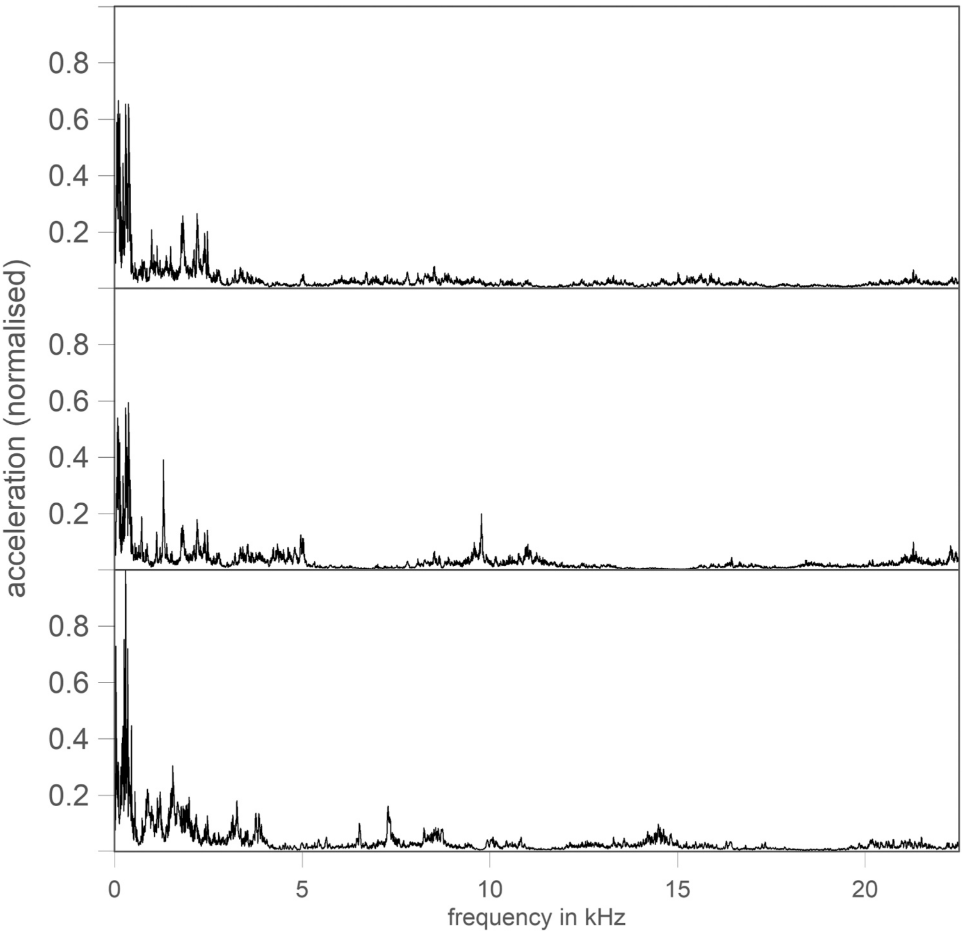

Fig. 10. Spectrum (up to 3 kHz) of the acceleration signal (over 10 s measurement run) at sensor ai0 - top, ai1 - middle and ai3 bottom for the average soil moisture.

cultivation. Particularly when sowing, the requirement of a seed placement depth at the soil moisture horizon is of central importance for rapid germination, good young plant development and thus for crop density and yield.

The results of the investigated acoustic approach for the online detection of soil moisture show that the limitations of systems used to date or currently under development can be overcome. The use of comparatively very simple, robust measurement technology, which is used in almost all industrial sectors, is complemented by the results presented here in that the recorded measurement data show a clear increase in vibration acceleration amplitudes in both the time and spectral domain as soil moisture decreases. This is consistent with the observation that the moist soil has a sound-absorbing effect by itself and that increased damping can also be expected due to a good form fit between the soil and the tillage tool. In addition, the raised soil particles, which are generally smaller and softer, generate lower impulse forces in contact with the tillage implement and thus a reduced structure-borne noise input into the soil tillage machine. Furthermore, it can be assumed that the observed vibration behavior is due to the fact that as the soil becomes drier, the forces required to process or loosen the soil and thus also the input of dynamic forces into the soil tillage tool or implement increase accordingly.

With the soil tillage implement used, the range up to 3 kHz is initially very relevant, but the range above this up to over 20 kHz also shows the dependence on soil moisture. As each frequency point carries specific information, it becomes clear how much more powerful this system is compared to the measurement of a single electrical conductance value, for example. It could be shown that sensors at different positions of the device show equally meaningful signals and provide vibro-acoustic information. Even a very simple analysis of the time data, by calculating the RMS value of the data from a measurement window and relating it to the soil moisture values measured at specific points, results in an R^2 value of 0.645. If the data is differentiated according to the crossings, the R^2 values increase to approx. 0.72. If the data is viewed in stages, so that measurement points with closely aligned soil moisture values to each other are grouped together, the R^2 value increases to 0.933.

In addition to soil moisture, there are other parameters that influence the vibration behavior in particular the soil type and structure, the working depth and the speed. Further investigations must be carried out in the future under a wide range of boundary conditions e.g. type of soil in order to optimize the system in this respect. The broader applicability of these findings can be achieved by calibrating the sensors for different soil types, textures and structures. In addition to soil water content, soil texture, chemical cementation (Liu et al., 2022) and compaction affects the cohesion and strength of the soils (Shakoor, 2018), which consequently affects the vibration of the soil equipment. The calibration method for different soil textures is described in an invention of the authors of this work, filed on 14 November 2024 with the European Patent Office under the designation European patent application EP 24213049.0.

The use of machine learning techniques might be conceivable as an extension. For example, in the forage harvester, many factors influencing the acoustics, such as moisture of the harvested material, throughput, sand and soil content in the crop, driving speed, could be successfully analysed using an analysis method based on machine learning using the acoustic data (Schneider et al., 2024a and Schneider et al., 2024b).

With regard to the working depth the method is not limited to a

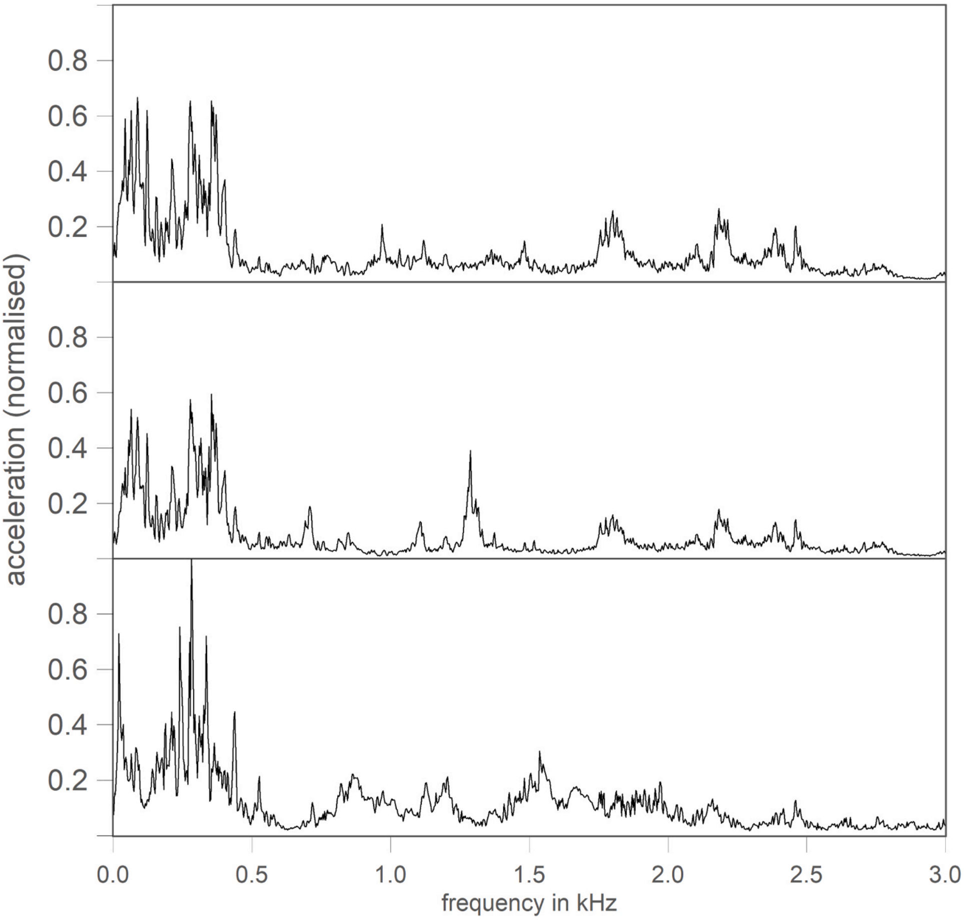

Fig. 11. Spectrum (up to 3 kHz) of the acceleration signal (over 10 s measurement run) at sensor ai0 - top, ai1 - middle and ai3 bottom for a medium soil moisture level.

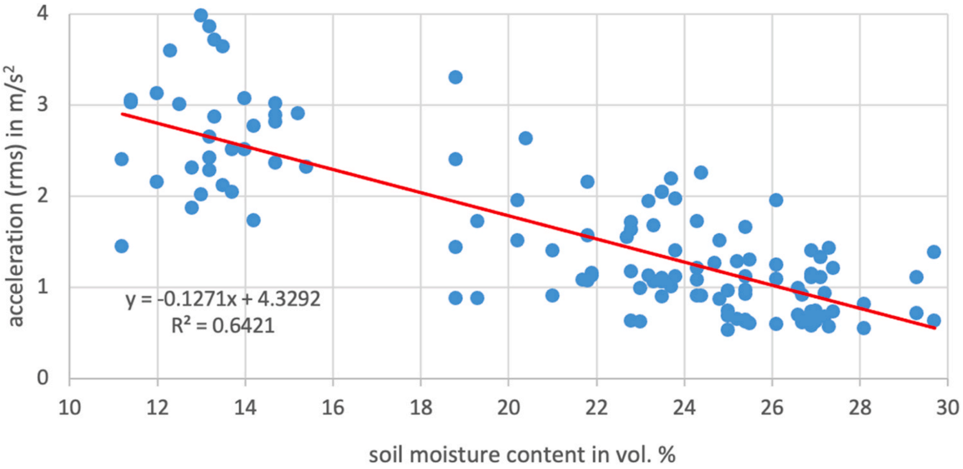

Fig. 12. Mean RMS values of the acceleration signal at sensor ai0 for one time window for all soil moisture values investigated (for one row) including the first or second pass.

depth of 13 cm. It has been chosen because it is a typical depth for tillage, so of course the method can be carried out in the same way for different depths. Due to soil behaviour at different heights, it is clear that different sound responses can be observed and we have considered extending our scientific observations to greater depths up to a maximum of 1 m, where typical soil is limited. Typical soil behaviour is measured at 30 cm or 90 cm depth. So this would be a good starting point for further measurements. The question to be answered, of course, is what relevance this will have to agriculture in the future as more sophisticated farming methods are developed. One aim of real-time monitoring is to identify the best depth for sowing. A calibration curve can be developed to show the relationship between vibro-acoustic sensors and soil moisture for each soil and soil depth.

To increase the robustness of the acoustic system, for future studies it is planned to repeat the studies in different geomorphological conditions. Of course, it would be a major section of soil research to take into

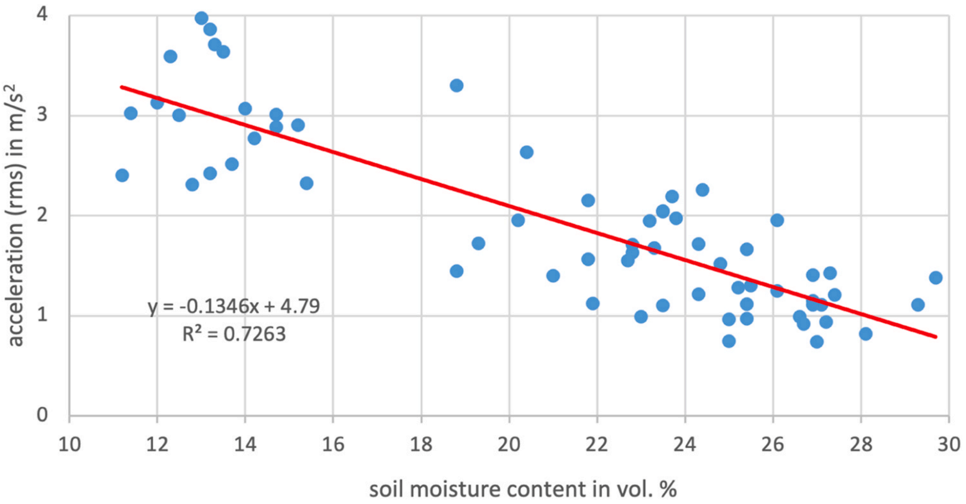

Fig. 13. First pass: average RMS values of the acceleration signal at sensor ai0 for one time window each for all soil moisture values investigated (for one row).

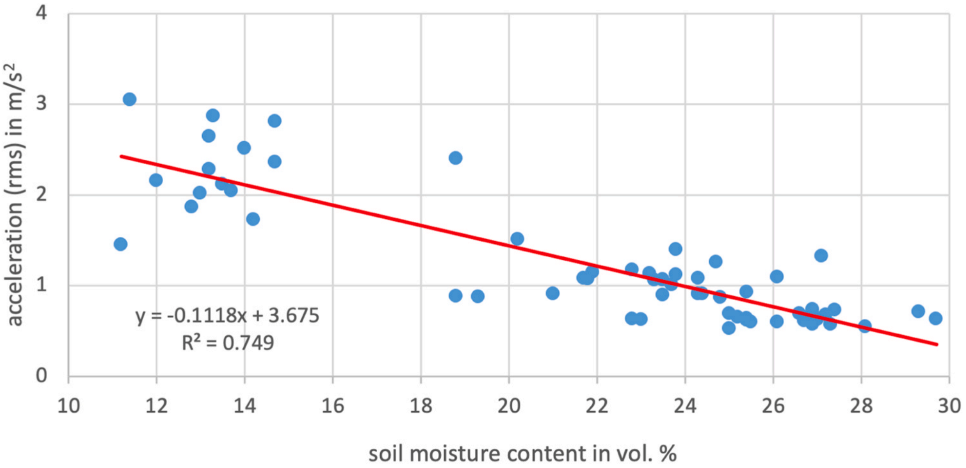

Fig. 14. Second pass: average RMS values of the acceleration signal at sensor ai0 for one time window for all soil moisture values investigated (for one row).

account all the physical conditions of the soil.

Of course, the speed also has an effect on the acoustic measurement. As reported by Gao et al. (2024), tractor speed influences the vibration characteristics at the rotary tiller. The tests were carried out at a speed of 3 km/h for practical reasons. However, the method will undoubtedly work at different speeds as required in different farm applications. Considering that the acoustic damping of the soil is constant due to the water content in the pores of the soil, the influence of increasing the working speed of the tractor will result in higher forces on the tillage implement and then, of course, consequently in higher forces to be realized in the tillage implements, for example ploughshares. The acoustic response function created by this physical-mechanical behavior could result in higher amplitudes due to higher acceleration of the structure-borne sound. A further effect could be realized by hitting stones on the shares at the moment of acoustic monitoring of the structure borne sound on the shares. However, future studies could explore varying tractor speeds tailored to different agricultural operations.

It is expected that the tool design will also have a significant influence on the vibration signal amplitude. At this point, it is necessary to carry out more intensive soil studies to understand the effect of different geometries in vibrating tools. For example, one of the questions to be answered could be how a surface augmentation of the vibrating soil tillage tool affects the signal in its frequencies and amplitudes as a function of different soil types and soil moisture levels.

In a later application, it would be conceivable to mount an additional tine on the machine, which is equipped with a corresponding sensor system including evaluation electronics and serves the sole purpose of detecting soil moisture. Practical issues such as sensor stability, durability or maintenance obviously have an important influence on the measurements. The measurements were carried out with laboratory sensors to obtain the best results. In a more practical and consumer friendly way, the sensors need to be replaced by more practical fitting sensors such as knock sensors or industrial acceleration sensors in general. Piezoelectric accelerometers have proven themselves in many long-term use in harsh industrial environments and are therefore comparatively inexpensive and available in a robust design. The physical measuring principle or sensor concept is the same, the piezo effect. But of course the industrial proven sensors are more robust and can be adapted to various stressful applications and will not be destroyed as quickly as high sensitivity laboratory sensors. As the sensors are screwed to the top of the vibrator, they can be replaced very quickly if required. The information is transmitted to the tractor via an Isobus interface, where it is used as setting information for the driver in a corresponding display unit, or the signal is taken directly from the machine control system, for example for automated adjustment of the working depth or tool pressure. The design of this tine could be accompanied by an acoustic FEM analysis for an optimally adapted design. A subsequent modal analysis can be used to determine the actual resonances that occur and to adjust the measurement and analysis system accordingly.

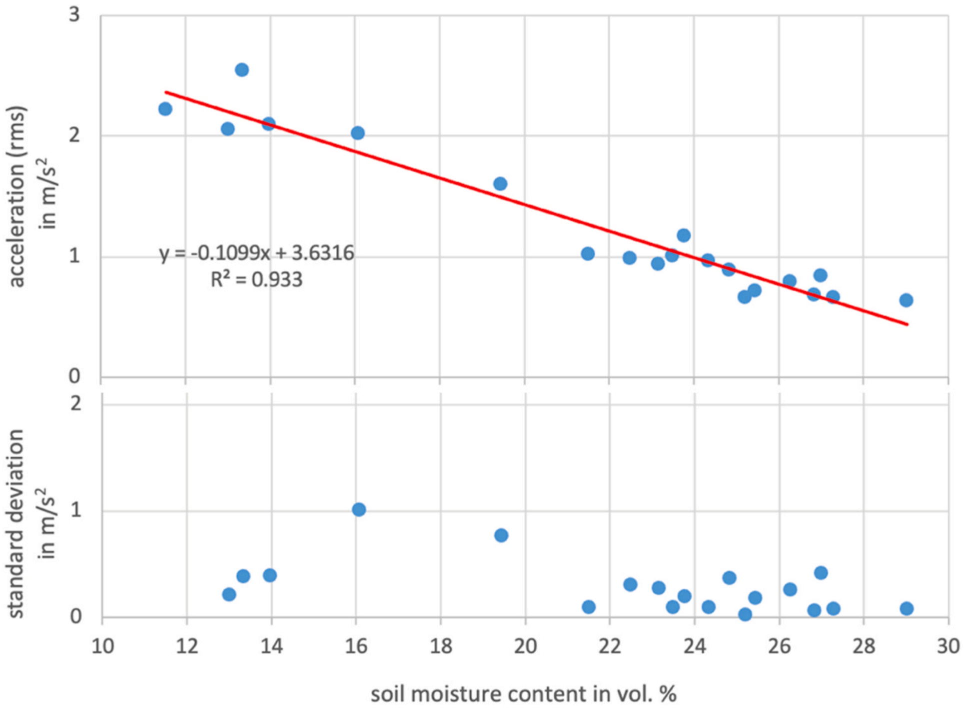

Fig. 15. Second pass: average RMS values of the acceleration signal at sensor ai0 for one time window for all soil moisture values investigated (for one row).

CRediT authorship contribution statement

Hensel Oliver Prof.: Writing – review & editing, Supervision, Methodology, Conceptualization. **Nasirahmadi Abozar:** Writing – review & editing, Supervision, Conceptualization. **Bilibio Carolina:** Writing – review & editing, Methodology, Conceptualization. **Siebald Hubertus Kurt:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Kaufmann Hans-Hermann:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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