Theoretical and experimental investigation of Continuous Compaction Control (CCC) systems

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ABSTRACT
Continuously improved compaction techniques in earthworks and geotechnical engineering require the use of adequate test equipment to assess the achieved compaction success. Conventional and spot like compaction testing methods, especially at large construction sites, are outdated and do not represent the state of the art anymore. Therefore, Continuous Compaction Control (CCC), a roller integrated system, has become the commonly used method for compaction control with vibratory rollers.
In the presented paper the leading CCC systems on the market (Compactometer, Terrameter, ACE) are discussed. Their structure, measurement principle and theoretical background is investigated.
Moreover, large-scale in situ tests were performed with a tandem roller with an oscillating and a vibrating drum. For the first time all three CCC systems and four CCC values are calculated from the accelerations of one single roller. The results of these large-scale tests are compared, dependencies of the CCC values on excitation parameters are investigated and advantages and disadvantages of the CCC systems are outlined.

Keywords: soil dynamics, compaction, roller, vibration, Continuous Compaction Control.

1 INTRODUCTION

Continuous Compaction Control (CCC) is the state of the art method for the assessment of the achieved compaction success with vibratory rollers. CCC is, as the name suggests, a roller integrated compaction measurement method for dynamically excited rollers, that allows to measure the compaction success online and continuously and to document the results during the compaction process. CCC systems measure the accelerations in the bearing of vibratory drums and analyze the motion behavior of the drum to calculate a stiffness proportional CCC value.
There are currently three leading CCC systems on the market, the Compactometer, the Terrameter and the ACE system, which differ in their measurement principle and theoretical background.
These differences are investigated within this paper. Moreover, results of large-scale in situ tests are presented, where all three CCC systems and four CCC values were calculated from the accelerations of one single roller for the first time.

2 VIBRATING ROLLERS

Vibration is the commonly used type of excitation for dynamic drums. The biggest advantage of vibrating rollers in earthworks is their significantly higher vertical loading, which results in larger compaction depths.

2.1 *Principle of vibrating rollers*

The eccentric masses of a vibrating drum are shafted concentrically to the drum axis, resulting in a mainly vertical loading of the soil. This implies the main characteristics of vibrating drums, the lager compaction depth and higher ambient vibrations compared to oscillating rollers.

2.2 *Modes of operation*

The vibrating drum and the compacted soil form an interacting system, where the soil starts to vibrate because of the drums excitation, but also influences the drums motion behavior. The soil stiffness, the speed of the roller, the excitation frequency and the ratio between roller and drum mass have a significant impact on the interacting system of drum and soil. Depending on these factors typical modes of operation can be identified (see Figure 1).

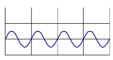
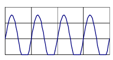
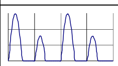
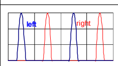
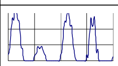
drum motion	Interaction drum-soil	operating condition	soil contact force	application of CCC	soil stiffness	roller speed
periodic	continuous contact	CONT. CONTACT		yes	low	fast
	periodic loss of contact	PARTIAL UPLIFT		yes	↓	↑
		DOUBLE JUMP		yes	↓	↑
		ROCKING MOTION		no	↓	↑
chaotic	non-periodic loss of contact	CHAOTIC MOTION		no	high	slow

Figure 1 Modes of vibratory roller operation (Adam, 1996).

Continuous Contact
No loss of contact can be observed in the mode of operation “Continuous Contact”. Therefore, the soil must be able to follow the drum motion, which only is the case for very soft soils and loose fillings or small excitation amplitudes.

Partial Uplift
The mode of operation “Partial Uplift” is the typical mode of operation for well designed rollers and also the most efficient mode of operation for vibrating rollers. The increasing vertical force pointing upwards causes a periodic loss of contact between drum and soil in each period of excitation.

Double Jump
If the soil stiffness increases, the drum motion only reproduces with every second period of excitation. The drum is also uplifted during the mode of operation “Double Jump”, but falls back on the soil with one strike of high impact and one strike with lower impact. The high energy transmitted into the soil by the high impacts results in a high compaction. However, it also causes a significant higher wear of the roller, as well as increased ambient vibrations.

Rocking Motion
If the soil stiffness increases further, the longitudinal axis of the drum is alternately tilted to one side and the other and a phase shift in the motion behavior of the drums left and right side can be observed.
The roller can hardly be handled in “Rocking Motion” and controlled compaction work is not possible any longer.

Chaotic Motion
A combination of very high soil stiffness and unfavourable compaction parameters (large amplitude, high frequency, low speed) can cause “Chaotic Motion”. The motion behavior is not periodic any longer and a roller handling is not really possible. Rocking motion and chaotic motion have to be avoided.

3 CCC FOR VIBRATING ROLLERS

3.1 *Basic principle, components and existing CCC systems*

In contrast to spot like testing methods the CCC is a roller and work integrated method for the assessment of the soil stiffness. The roller is not only used as a compaction device, but also serves as a measuring device at the same time.
The basic principle of a CCC system is to assess the soil stiffness by evaluating the motion behavior of the drum. The parameters that influence the motion behavior of the drum also influence the values of CCC systems. Therefore, the first condition for a CCC system is to keep the rollers properties

of the compaction process like speed, excitation frequency and excitation amplitude constant during the CCC measurements. The second condition for a CCC system is the recording of the motion behavior of the drum. This condition can be fulfilled by recording the accelerations, velocities or displacements of the drum. Usually the accelerations are measured in the bearing of the drum in vertical and sometimes also horizontal direction.
The second part of a CCC system is a processing unit that calculates the corresponding CCC value for the piecewise analyzed acceleration signal (e.g. one CCC value for the time of two excitation periods). The processing unit also saves the CCC values. Moreover, a display unit is used to show the calculated CCC values online. Early CCC systems used sensors for distance and speed to assign the CCC values to a certain position on the construction site. Modern CCC systems use GPS for an exact assignment of the CCC values.
The first CCC system was built in the late 1970ies. Dr. Heinz Thurner noticed a correlation between the soil stiffness and the motion behavior of a Dynapac vibratory roller during experimental field tests in 1974. He later developed the first CCC system, the Compactometer, together with Dr. Åke Sandström, Dr. Lars Forssblad and Dynapac (Thurner, 1978).
In 1982 the Bomag GmbH presented the Terrameter, an alternative CCC system, which analyzes the accelerations in the time domain to calculate the *OMEGA* value . In the late 1990ies Bomag improved the Terrameter and presented the vibration modulus E_{vib}.
The ACE-System of the swiss Ammann AG Group was introduced in 1999. It calculates the k_B value by analyzing the vertical accelerations in the time domain.

3.2 Compactometer

The processing unit of the Compactometer performs a piecewise fast Fourier transformation (FFT) of the measured vertical acceleration in the bearing of the drum to evaluate the shares of the FFT spectrum at the excitation frequency and its multiples. Thurner and Sandström recognized a correlation between the relation of the shares at the excitation frequency and two times the excitation frequency and the soil stiffness.
Therefore, Thurner and Sandström defined the *CMV* (Compaction Meter Value) of the Compactometer as:

$$CMV = \frac{a(2w)}{a(w)} 300 \tag{1}$$

Where $a(2w)$ is the share at two times the excitation frequency and $a(w)$ is the corresponding share at the excitation frequency.
If the roller operates in the Double Jump mode, a peak at the half of the excitation frequency can be seen in the FFT spectrum. A second value, the *RMV* (Resonance Meter Value), was defined to detect the Double Jump mode:

$$RMV = \frac{a(0.5w)}{a(w)} 100 \tag{2}$$

The Compactometer was the first CCC system and is still used by the roller manufacturers Caterpillar, Dynapac, Hamm and Volvo.

3.3 Terrameter

The Terrameter analyzes the equilibrium of forces on the drum in vertical direction (see Figure 2).

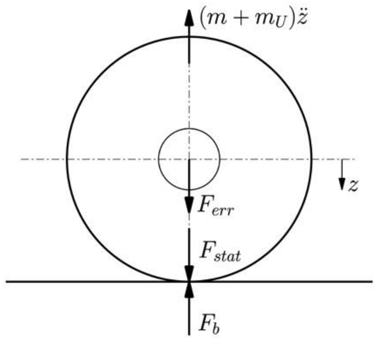


Figure 2 Equilibrium of vertical forces on the drum for the calculation of F_b.

The soil contact force F_b is calculated from the vertical acceleration $\ddot{z}$ under consideration of the static load F_{stat}, the excitation force F_{err}, the mass of the drum m and the eccentric masses m_U:

$$F_b = -(m+m_U)\ddot{z} + F_{stat} + F_{err} \quad (3)$$

The displacements z can be obtained from a two times integration of the acceleration signal. The displacements z and the soil contact force F_b can be used to draw a force-displacement diagram for each period of excitation (see Figure 3).

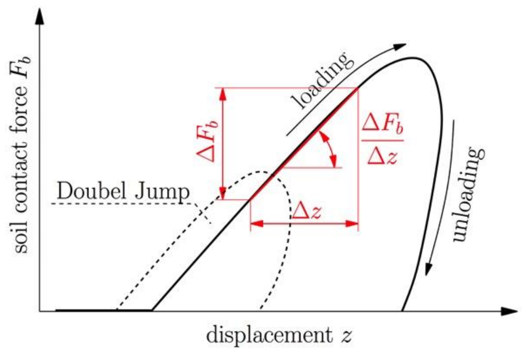


Figure 3 Force-displacement diagram of the vibrating drum for the calculation of OMEGA and E_{vib}.

The force-displacement diagram in Figure 3 is the basis for the CCC values *OMEGA* and E_{vib}.
The *OMEGA* value was the first CCC value of the Terrameter. It is the area under the force-displacement diagram for two consecutive excitation periods T_E:

$$OMEGA = factor \oint_{2T_E} F_b z \, dt \quad (4)$$

OMEGA is proportional to the energy transmitted into the soil.
The newer CCC value of the Terrameter system, the vibration modulus E_{vib} (MN/m^2) describes a soil stiffness by analyzing the inclination of the force-displacement curve between two defined points (40% and 90% of the maximum contact force). The E_{vib} is calculated recursively using a Poisson's ratio of $\nu = 0.25$:

$$\frac{\Delta F_b}{\Delta z} = \frac{E_{vib} 2 b_0 \pi}{2(1-\nu^2)\{2.14 + 0.5 \ln C\}} \quad (5)$$

with:

$$C = \frac{\pi (2b_0)^3 E_{vib}}{16(1-\nu^2)(m+m_U+m_R)gr} \quad (5)$$

Where r and b_0 are the radius and the half width of the drum respectively.

3.4 Ammann Compaction Expert (ACE)

The ACE system calculates the k_B value (MN/m) by processing the acceleration signals in the time domain. The significant point in the force-displacement diagram for the evaluation is the change from the loading to the unloading phase, where the displacement has its maximum and $\dot{z} = 0$ (see Figure 4).

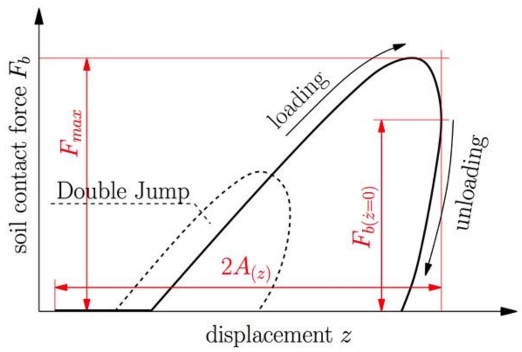


Figure 4 Force-displacement diagram of the vibrating drum for the calculation of k_B.

The ACE system uses two different equations for the calculation of k_B depending on the mode of operation. For continuous contact the k_B value can be calculated as:

$$k_B = \omega^2 \left[(m+m_U) + \frac{(m_U e_U Vario)\cos\varphi}{A_{(z)}} \right] \quad (5)$$

Where $A_{(z)}$ is the amplitude of the displacement and φ is the angle of phase shift (see Figure 5).
In case of a periodic loss of contact, the k_B value is calculated using the contact force at the change from the loading to the unloading phase $F_{b(\dot{z}=0)}$:

$$k_B = \frac{F_{b(\dot{z}=0)} - (m+m_U+m_R)g}{A_{(z)}} \quad (5)$$

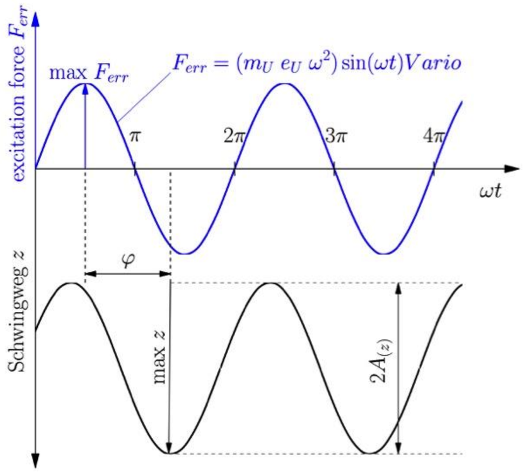


Figure 5 Excitation force F_{err} and displacement z for the calculation of k_B.

4 EXPERIMENTAL FIELD TESTS

4.1 Compaction device

A HAMM HD$^+$ 90 VO tandem roller was used as compaction device. The roller comprises a total mass of 9,830 kg and two drums of about 1,900 kg vibrating mass each. The typical speed during compaction work for this type of roller is 4 km/h and was used throughout the majority of the tests.
Depending on the rotational direction of the eccentric masses, the vibratory drum at the front of the roller operates with a vertical amplitude of 0.34 mm or 0.62 mm respectively. For the smaller amplitude a frequency of 50 Hz was used most of the time, while 40 Hz was the standard frequency for vibratory compaction with the large amplitude.
The drum on the rear of the roller is an oscillatory drum that uses a tangential amplitude of 1.44 mm.

4.2 Test layout and measuring equipment

A test area was prepared and equipped in a gravel pit near Vienna for the experimental field tests. The test area comprised four parallel test lanes of loose sandy gravel (to be compacted) with a length of 20 m and a thickness of 0.5 m (see Figure 6). The test field was filled on the highly compacted plane of the gravel pit. The typical layer thickness for compaction with the used roller ranges from about 20 cm to 30 cm. However, the thickness was chosen larger to be able to run more tests without over-compacting the layer. The four test lanes were intended for static, vibratory, oscillatory, and combined vibratory and oscillatory compaction. Two ramps at the beginning and at the end of the test lanes served for roller handling, speeding up and down the roller as well as for lane changes.

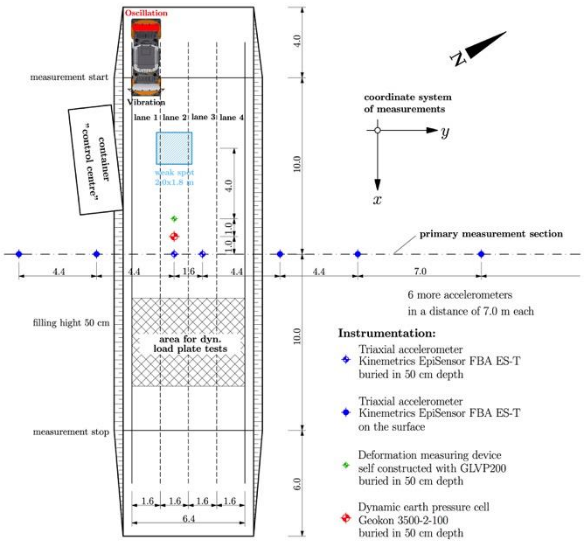


Figure 6 Test layout of the experimental field tests (Pistrol, 2015).

The test field was equipped with tri-axial accelerometers, a deformation-measuring-device and an earth pressure cell to evaluate the impact of the roller on the soil and the surrounding area. The results of these measurements are not discussed within this paper but can be found in Pistrol et al. (2013), Pistrol et al. (2015) and Pistrol (2015).
Two conventional mattresses were buried in a depth of 0.5 m under test lane 2 to simulate a uncompacted, weak spot in the test field and to investigate its influence on the CCC values (see Figure 6).
The vibratory drum of the roller was equipped with 4 accelerometers with a sensitivity of ± 30 g. The accelerometers were mounted on the left and right side bearing of the drum to measure the accelerations in horizontal and vertical direction on the undamped drum. The accelerometer signals were recorded with a sampling rate of 1,000 Hz.

The tandem roller also had a preinstalled Compactometer CCC system which was used as a reference for the calculation of the CCC values.

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5 RESULTS OF THE EXPERIMENTAL FIELD TESTS

The results of the experimental field tests are discussed in the final paper…

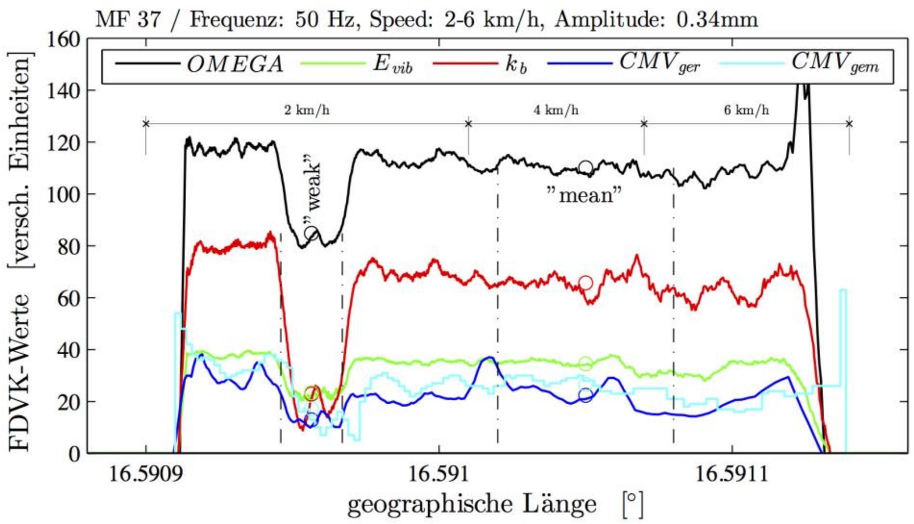

Figure 7 Force - displacement diagram of the vibrating drum for the calculation of k_B.

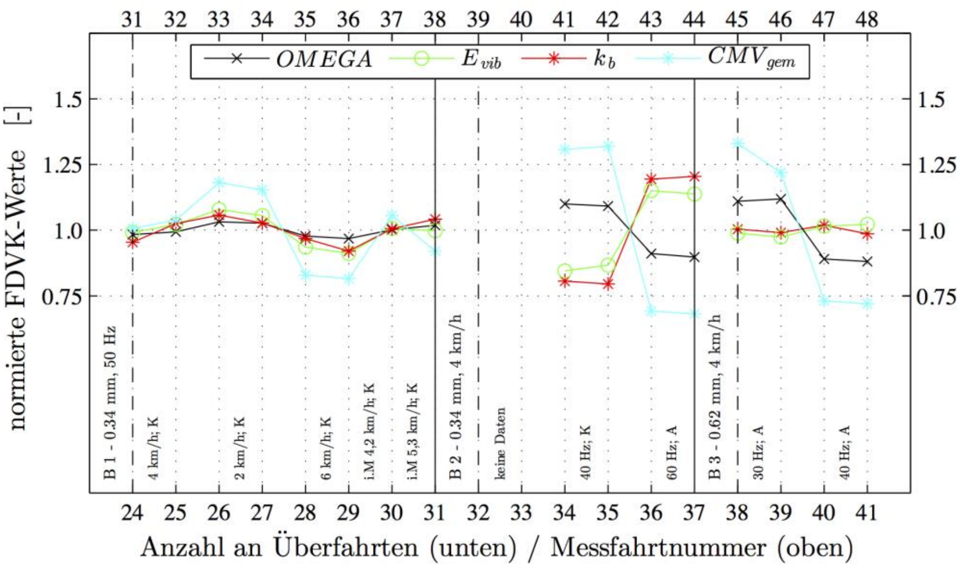

Figure 8 Force - displacement diagram of the vibrating drum for the calculation of k_B.

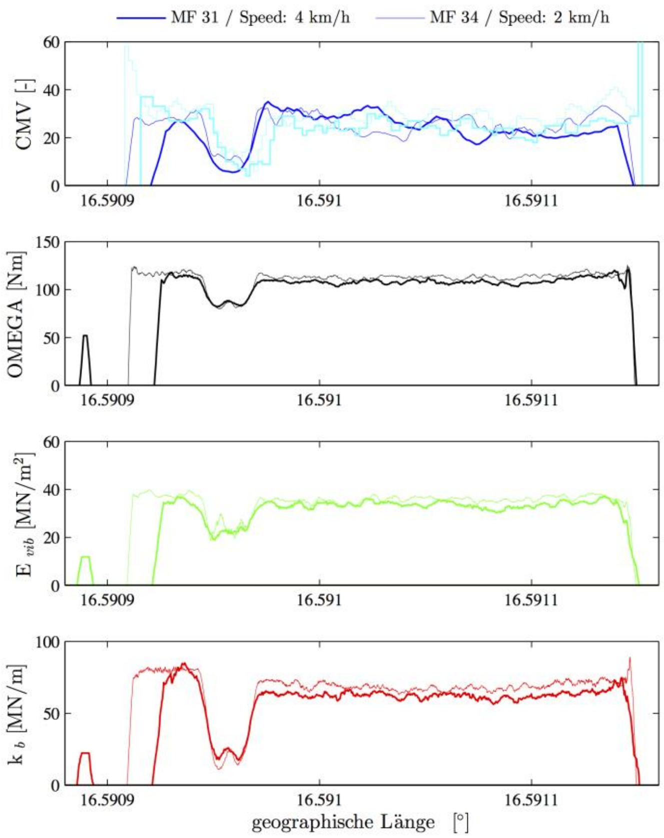

Figure 9 Force - displacement diagram of the vibrating drum for the calculation of k_B.

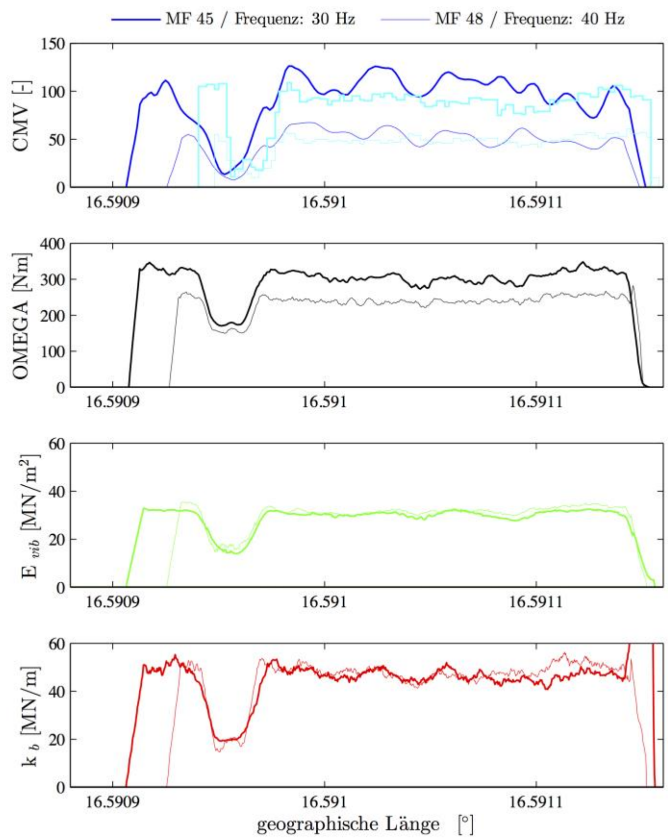

Figure 10 Force - displacement diagram of the vibrating drum for the calculation of k_B.

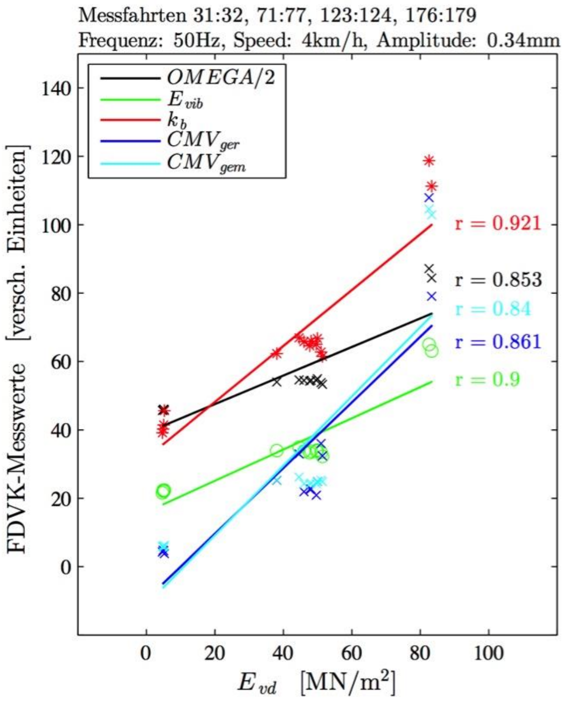

Figure 11 Force - displacement diagram of the vibrating drum for the calculation of k_B.

6 CONCLUSIONS

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