Control of Working Regime of Vibratory Roller in Compaction Process

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Abstract: *Road construction involves strict control methods regarding the quality of terrain compaction works (both soil and asphalt mixture). The paper presents systems for controlling the vibration characteristics for the working regime of vibratory roller compactors. Essential parameters (vibration amplitude, compaction energy, performance compaction, process efficiency) are highlighted that form the basis for calculating some compaction quality indicators used in algorithms for automatic control of the machine's working regime in continuous correlation with the characteristics of the terrain under roller action. Hydraulic drive systems in vibratory drum compactors precisely control the frequency and amplitude of the drum vibrations, which optimizes the compaction process for different soil types, ensuring better efficiency and less wear on the machine. Computer simulation helps predict how a compactor will perform under different conditions (e.g., varying frequencies and amplitudes) to establish optimal operating parameters for specific projects.*

Keywords: *Roller, compaction, vibration, control, quality*

1. Introduction

Quality control and quality assurance (QA/QC) of the compaction process are indispensable for the long-term performance of roads or foundation works [1,2]. With technical progress in the field of automation and information processing, intelligent technology has been implemented on the compaction machines, which has great potential to solve some of the shortcomings of the classical standardized methods for evaluating the quality of the compaction process. Currently, high-performance compaction equipment has implemented systems that adjust the working frequency of the vibratory roller depending on the degree of compaction of the layer, improving the efficiency of the technological process. Table 1 lists manufacturers of compaction equipment that have developed automatic adjustment systems for operating parameters.

Table 1: Examples of roller vibration control systems

Manufacturer	System name	Monitored parameter
Bomag	Economizer, Variocontrol, Asphalt manager	Evib (Vibratory Modulus)
HAMM (Wirtgen Group)	HCQ / Smart Compaction / Smart Compact	CMV (Compaction Meter Value), Evib (Vibratory Modulus), ICMV (Intelligent Compaction Measurement Value)
Caterpillar (CAT)	CAT Compaction Control (AccuGrade Compaction)	MDP (Machine Drive Power), CMV (Compaction Meter Value), Global Navigation Satellite Systems
Dynapac	Compaction Analyzer System (COMPAS)	CMV (Compaction Meter Value), Evib (Vibratory Modulus)
Ammann	Ammann Compaction Expert (ACE)	Evib (Vibratory Modulus)
Sakai America	CIS (Compaction Information System)	CCV (Compaction Control Value)
Volvo Construction Equipment	Intelligent Compaction	MDP (Machine Drive Power), Evib (Vibratory Modulus), CMV (Compaction Meter Value)

The operating principle of these systems consists of continuous monitoring of the interaction between the drum and the soil by measuring with help of the sensors mounted on the drum various parameters (like stiffness, power consumption etc.) and automatic adjustment of the required compaction energy. The advantages that this mode of operation of the vibratory regime of the working tool of a compactor brings are [3]:

- Directional vibration, which automatically adapts to the direction of travel.
- Maximum efficiency as the energy is concentrated to achieve optimal compaction with a minimum number of passes, even in thick fill layers, increasing compaction performance by up to 30% compared to standard systems.
- Adaptive control that allows controlled, strong compaction in open areas and gentle compaction near sensitive structures, by simply automatically adjusting the vibration amplitude (see Figure 1).
- Database with compaction information (Evib, MDP, CCV, number of passes etc.) in real time.

Fig. 1. Adjustment of vibration characteristics

In practice on construction sites, the integrated systems (especially based on Fuzzy Logic, Artificial Neural Networks and Reinforcement Learning) on this type of equipment use sophisticated, calibrated algorithms and inter-parametric variation laws, with the aim of converting data acquired by sensors (acceleration, speed, resistance force) into various compaction indices necessary for the operator to know the stage of compaction of the material at any time [4].

2. Hydraulic drive systems for control vibration

The hydraulic system for driving the eccentric masses inside the roller of vibratory compactors operates on the principle of converting hydraulic energy into mechanical rotational motion, which generates the vibratory force. The main components of the hydraulic vibration system include the main hydraulic pump (usually with variable displacement pistons, driven by the compactor's diesel engine), the hydraulic vibration motor (often of the orbital or piston type) mounted directly on or near the eccentric mass housing in the drum, the eccentric masses (made of metal attached to a shaft, which generates a centrifugal force when the shaft rotates, thus causing the drum to vibrate, see Figure 2), hydraulic pipes and a control block for directing the flow of oil from the pump to the hydraulic motor and back to the tank, managed by a hydraulic distributor.

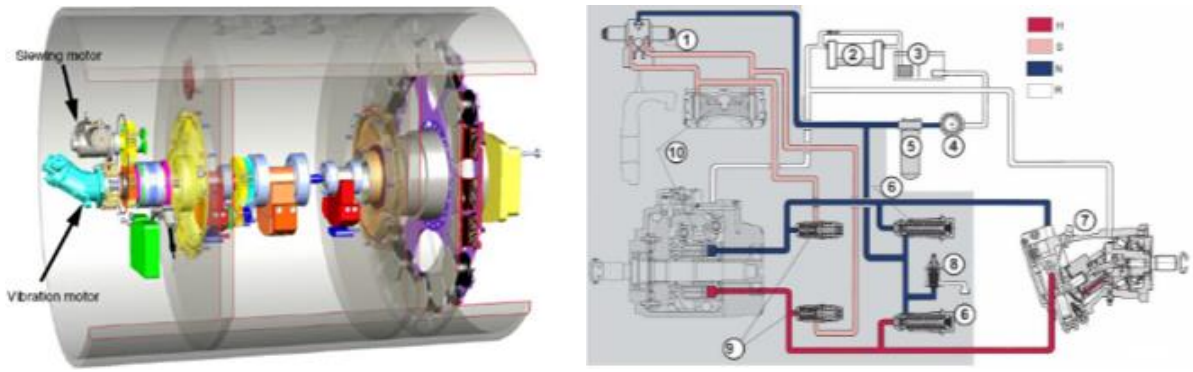

Fig. 2. Exciter unit from single vibratory drum with Vario Control (model Bomag) and description of the hydraulic system [5]: 1. Control unit; 2. Radiator; 3. Tank; 4. Charge pump; 5. Charge oil filter; 6. High pressure valves; 7. Hydraulic motor; 8. Charge valve; 9. Control pressure relief valves; 10. Servo control; 11. Servo adjustment plate.

The modern hydraulic systems allow precise adjustment of vibration parameters, such that:

- vibration frequency is controlled by adjusting the oil flow rate supplied to the hydraulic motor through the operator's command, who can increase or decrease the speed of the hydraulic motor (and implicitly, the speed of the eccentric masses) by varying the flow rate of the hydraulic pump.
- vibration amplitude is controlled by adjusting the position of the eccentric masses or, in some advanced systems (such as those with "split eccentric"), by changing the effective mass that generates the eccentricity. Some systems allow the operator to select high or low amplitude through additional hydraulic mechanisms that reconfigure the masses.

In addition, an intelligent hydraulic system can be closed-loop, proportionally controlled, which receives digital feedback from the ground and instantly adjusts hydraulic parameters (e.g. pressure, flow, vibration direction) to always apply the optimal amount of compaction energy. A simplified hydraulic diagram of such an intelligent system contains a Diesel engine, a main hydraulic pump (with variable flow, electronically controlled), a proportional control valve or electro-hydraulic proportional distributor (which receives electrical signals from the ECU and precisely modulates the flow and pressure to the vibration motor, allowing continuous adjustment of frequency and amplitude - when the soil is soft, the amplitude is high, and when the soil is stiff, the hydraulic system automatically reduces the vibration amplitude to the minimum necessary), a hydraulic vibration motor, an eccentric mass shaft, a roller, a sensor mounted on the roller (that measures various parameters in real time, see Table 1), an electronic control unit - ECU (which processes data from the sensor and sends electrical commands to the proportional valve to automatically adjust the vibration) and an oil tank.

It is observed that the key interaction is between the parameter measured by the sensor, the ECU and the control valve so that when the sensor detects that the soil is soft, the ECU commands the valve to allow a flow rate and pressure that generates a high vibration amplitude or vice versa, as the soil compacts and becomes stiffer, the sensor sends constant feedback to the ECU, which commands the valve to automatically reduce the amplitude, optimizing the applied energy and preventing over-compaction or unwanted resonance.

3. Simulation of the dynamic behavior of the vibratory drum

In systems mechanics, the simulation of dynamic behavior of the rollers is done on rheological models, simplified (with a single degree of freedom, 1DOF) or complex, considering the viscous and elastic characteristics (where applicable, plastic) for a better understanding of the phenomenon as a whole [6,7]. As an example, a simplified model for the study of the roller-soil interaction is considered given in Figure 3 with the equation of motion (1):

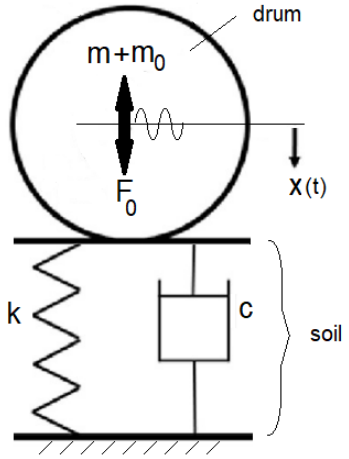

Fig. 3. Dynamic model with 1DOF for simulation of the vibratory drum operating

$$(m + m_0)\ddot{x}(t) + c\dot{x}(t) + kx(t) = F_d(t) \quad (1)$$

where *m* is drum mass, m_0 is the eccentric mass, *c* is the damping soil, *k* is the stiffness soil, *x* is the vertical motion of the drum, F_d is the dynamic force generating by the eccentric mass that is calculating with the formula

$$F_d(t) = F_0 sin\omega t = m_0 r\omega^2 sin\omega t \tag{2}$$

where *r* represents the eccentricity, ω is the angular velocity and *t* is the time.
In quality control of compaction and the technological process, evaluation of the power absorbed (P_t) by the compaction system is an indirect, but recommended indicator of the condition of the material being worked on. The acceleration values $\ddot{x}(t)$ measured by the sensor mounted on the roller are processed to determine the vertical vibration velocity obtained by integrating the acquired signal in time. The calculation of the power required for compaction consists of:

$$P_t(t) = F_d(t)\dot{x}(t), \tag{3}$$

where $F_d(t)$ represents the dynamic instantaneous force transmitted into soil by the vibratory drum.
This data allows as indicator of soil stiffness: as the soil becomes more compact, the resistance to penetration increases and, implicitly, the power required to maintain the same amplitude of vibration changes. This correlation is the basis for modern Intelligent Compaction (IC) systems. In addition, we can identify the optimal compaction point because the variation of required power throughout the compactor's passes indicates the moment the material has reached maximum density (or the desired degree of compaction), signaling to the operator when to stop working in a specific area and move to the next. In this way, it prevents over-compaction (which can damage the material's structure or the roller) or insufficient compaction.
The analysis in the phase plane of a compactor roller's vibrating movement aims to evaluate the dynamic behavior of the compactor-soil system and to determine the efficiency of the compaction process. Thus, by studying the trajectories in the phase plane (displacement and velocity), engineers can identify optimal settings for the frequency and amplitude of vibrations to ensure a maximum degree of compaction of the processed material. Therefore, with help of the phase plane method, it obtains information about stability and vibration regimes, being a classic method used for non-linear systems that allows the study of motion characteristics and equilibrium points, to determine the stability of the roller under various operating conditions. In addition, deviations from normal phase plane trajectories indicate also operational problems (such as bearing wear, imbalances or other mechanical failures), helping to diagnose the technical condition of the drum.
The compaction energy per unit volume (*E*) is expressed by a formula that considers many parameters involved in this technological process such as [8]:

$$E = \frac{2AfN(W + 0.25\pi F_d)}{Bhv} \tag{4}$$

where *A* is the amplitude, *f* is the working frequency, *N* is the number of passes, *W* is the roller weight, F_d is the dynamic force, *B* is the drum width, *h* is the layer thickness, and *v* is the travel speed. In advanced practical applications, especially in modern field compaction monitoring systems (such as Roller-Integrated Compaction Monitoring - RICM technologies), it can evaluate the compaction energy (*E*) by graphical integration (area calculation) of the soil transmitted force – drum vertical displacement curve (*x*)

$$E = \int F_d(t)dx. \tag{5}$$

For simulation, the technical data of a model BW 213 BVC (with Variocontrol system, Bomag) roller are used: axle load per drum (front) = 8500 kg, static linear load per drum = 39.9 kg/cm, **vibration amplitude =** 0 - 2.25 mm, frequency = 15 -25 Hz, **dynamic force (max.)** = 365000 N.
In Figure 4 are given the simulation results performed in Matlab environment software.

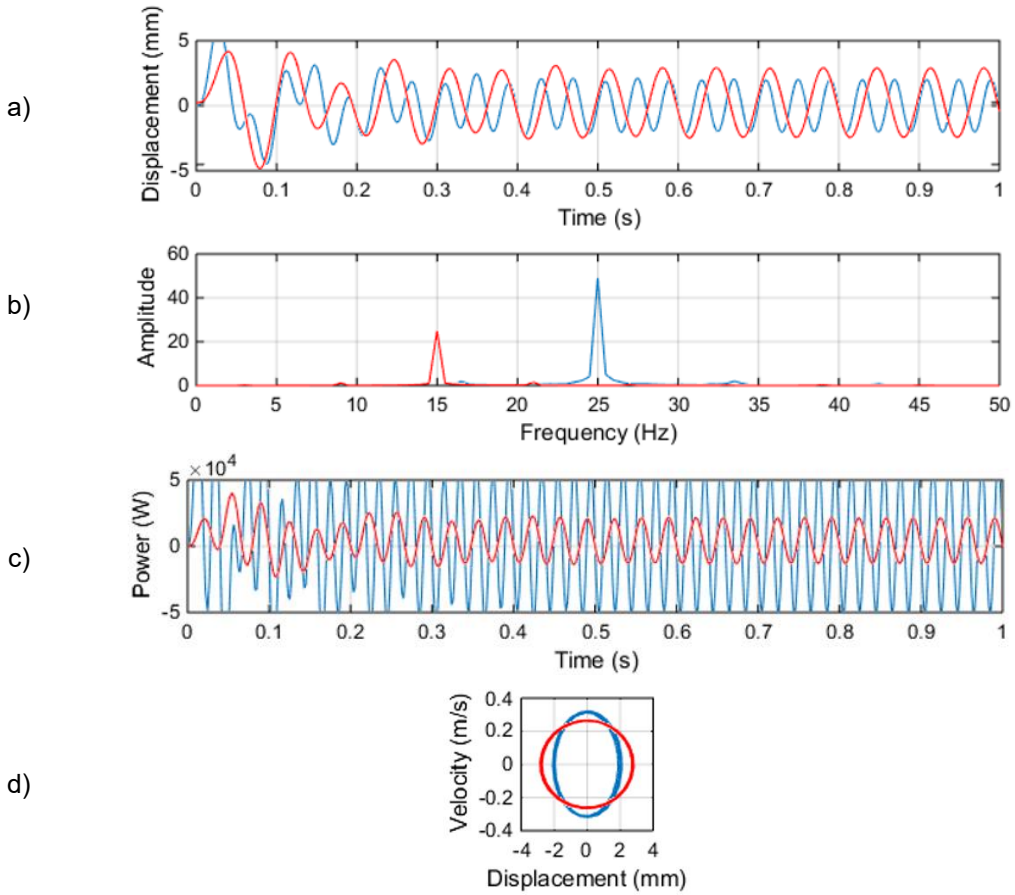

Fig. 4. Simulation results of the roller in compaction process in two working regimes (red – f = 15 Hz; bleu – f = 25 Hz. a) vertical displacement of the roller drum; b) spectrum frequency of the vertical acceleration of the vibratory drum; c) power consumption; d) analysis of phases of the plane of the drum motion.

The energy consumption during the 2.5-second in the high-frequency operating regime of the roller showed an increase of over 40% compared to the low-frequency regime, as shown by the results presented in Table 2.

Table 2: Energy compaction

Working frequence	*f* = 15 Hz	*f* = 25 Fz
Energy compaction	*E* = 11048.17 J	*E* = 15879.40 J

Another key metric for measuring efficiency and productivity on a project is performance (compaction output rate, Q_p) refers to the volume of soil that can be effectively and appropriately compacted per unit of time [9]. For example, the difference in performance between a compactor model Bomag BW 213 D (with a standard circular exciter system) and a BW 213 BVC (with a Variocontrol system) lies in the efficiency and adaptability of compaction energy transmitted by the drum into the soil [5]. The results of comparison for large volumes of material, such as 50000 m^3 of gravel, and after five passes, are given in the diagram in Figure 5. The relationship for performance calculation is

$$Q_p = \frac{(B-b)vh}{N} \tag{5}$$

where: *a* represents drum width (*B* = 2.13 m); *b* represents overlap of lanes (*b* = 0.13 m); *v* is operating speed (v = 0.83 m/s); *h* is layer thickness (h = 0.5 m for BW 213 D model and, respectively, *h* = 0.8 m for BW 213 BVC model); *N* – number of passes.
The total costs per hour (excluding labor costs) differ between the two compactors: the BW 213 D model costs €40 per hour, while the BW 213 BVC model costs €44 per hour. In conclusion, the results show that by using the more efficient BW 213 BVC compactor, the total project costs were

reduced by 37% compared to using the BW 213 D model. This saving is because the BVC model has a higher hourly operating cost, but the overall cost reduction is due to the increased productivity required to complete the compaction work, because of the implemented Variocontrol system.

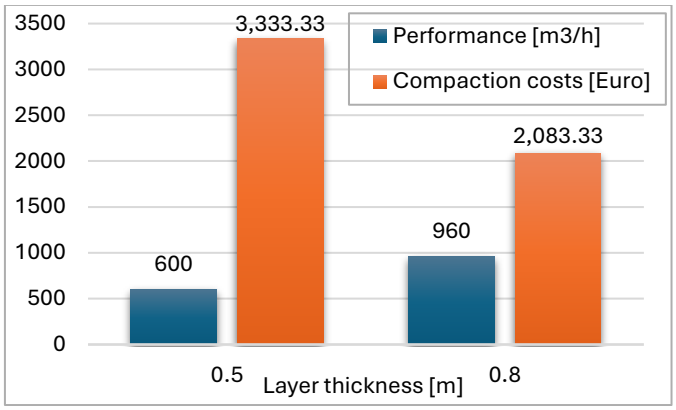

Fig. 5. Indicators for evaluating the quality of the compaction process

4. Conclusions

The paper presents recent technologies applied internationally in modern road and infrastructure construction aimed at ensuring the quality and uniformity of works, far exceeding the efficiency of traditional testing methods through point sampling. In advanced control systems that equip modern compactors, the physical/mathematical relationships between vibration parameters and soil properties constitute the key information upon which quality control in modern construction is based. This information allows for the continuous and automatic monitoring of the entire compacted surface. As a case study, some parameters (vibration amplitude, compaction energy, performance compaction, process efficiency) were obtained using a simulation process, based on the dynamic model with 1DOF associated with a type of vibratory roller. The advantage of systems for monitoring the parameters of the compaction process is that they provide information about the technological process in real-time, as well as enabling their management through an efficient management system.

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