Automated Data Acquisition and Statistical Analysis of Hydraulic Steering Systems Using Python and Arduino

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Abstract: This article discusses a comprehensive experimental study of the operational characteristics of the tractor prototype, with particular emphasis on the performance of its hydraulic steering system. The primary objective is to evaluate vehicle efficiency, directional stability, and dynamic response under a broad spectrum of operating conditions. Experimental measurements were conducted to quantify key steering parameters, including hydraulic pressure, flow rate, steering torque, and response time, as functions of engine speed and road surface characteristics. The influence of varying operating modes on steering behaviour was systematically analyzed to elucidate the coupling between vehicle dynamics and hydraulic control processes. The results demonstrate that changes in engine rotational speed and surface conditions significantly affect system load distribution and steering responsiveness. Nonlinear relationships between hydraulic parameters and vehicle operating states were identified, highlighting the complex interaction between mechanical and hydraulic subsystems. Statistical processing of the experimental data, combined with theoretical modeling, was employed to validate measurement reliability and ensure consistency of the obtained results. The findings provide valuable insights into the dynamic performance of hydraulic steering mechanisms and offer practical recommendations for improving design parameters, optimizing control strategies, and enhancing operational reliability. The outcomes of this research contribute to ongoing advancements in steering system development, supporting increased operational efficiency, reliability, and durability in practical applications. Future work may focus on integrating intelligent sensing technologies, predictive diagnostics, and real-time control strategies to further enhance steering precision and adaptability in next-generation vehicles.

1 INTRODUCTION

In intensive orchards and vineyards, the space for vehicle movement is extremely limited, and it is not advisable to use tractors designed for simple general work. Modern horticulture and viticulture require special, high-power, narrow-track tractors.

The main characteristic of specialized orchard and vineyard tractors is their compact construction, enabling efficient operation in confined spaces through short wheelbases, reduced width and height, and small wheels [1], [2]. Advanced steering technologies such as SuperSteer, used on tractors by New Holland Agriculture, can reduce turning radius by about 15% (from 3.4 m to 2.9 m), while articulated-frame designs applied by manufacturers like BCS and Landini can decrease it further to approximately 2.4 m [1].

Vineyard applications impose stricter dimensional requirements; in elite vineyards with row spacing of about 1.5 m, tractor width must not exceed roughly 1.08 m. Major manufacturers, including AGCO (Fendt 200 series) and New Holland (T4 series), therefore produce specialized variants such as F, V, P, and N types. Orchard-type tractors are generally wider and heavier than vineyard models. For instance, New Holland T4 orchard versions have a minimum track width of 1.44 m, compared with

1.18 m for vineyard versions, while the Fendt 200 Vario line ranges from 1.07 m in vineyard configurations to 1.68 m in high-capacity variants. In extreme narrow-row conditions, tractors equipped with reversible control posts can be operated in reverse without loss of speed or handling and enhancing operational flexibility [1].

When selecting garden machinery, not only overall dimensions but also machine weight must be considered, as excessive mass can cause soil compaction, leading to degradation and reduced productivity. According to [1], one recommended solution is the use of wider tires to distribute load more evenly over the soil surface.

The German manufacturer Claas has recently entered the low-power garden tractor segment with its Nexos technology, whose models effectively operate in intensive orchards and vineyards (Fig. 1). Similarly, Deutz-Fahr offers specialized 5DV/DS/DF TTV tractor series designed specifically for horticultural and viticultural applications. Indeed, The Deutz-Fahr 5D TTV series includes compact tractors with outer widths from 1077 mm to 1441 mm, offering flexibility through varied equipment and hydraulic options. Likewise, the Fendt 200 V/F/P Vario line represents the company's most compact tractors, specifically designed for orchard and vineyard applications, reflecting the demand for efficient and adaptable machinery in specialized agriculture (Fig. 2). In October 2021, a new generation of such machines was introduced, comprising five models with widths from 1.07 m to 1.68 m and engine power ranging from 79 to 124 hp.

Figure 1: Claas nexos tractor.

Figure 2: Fendt 200 F tractor.

Several Italian tractor models designed for specialized agriculture were analyzed [3]. The Q110 series by Goldoni features a sloped body design, reduced turning radius, near-isodiametric all-wheel-drive tires, and a 102 hp engine, making it suitable for narrow orchard and vineyard rows with limited clearance and uneven terrain. It also includes a low-profile 180 cm cabin.

The Rex4 series from Landini is intended for specialized farms and includes four variants. The F version is designed for orchards with minimum row widths of 1342 mm, while the V version, only 1003 mm wide, is optimized for vineyards. Its dual-pump hydraulic system supplies 50 L/min to rear implements and auxiliary systems and 28 L/min to steering. The SRX 10900 R tractor by Antonio Carraro represents a modern engineering solution for confined agricultural spaces. Figure 3 shows the Landini Rex V/S cab/plat series tractor, which is one of the specialized narrow tractors considered in this analysis. Its articulated frame, low center of gravity, and reversible drive system ensure high maneuverability and operational flexibility when performing tasks such as cultivation, spraying, towing, and loading [4], [12].

Figure 3: Landini Rex V/S cab/plat series tractor.

Thus, research shows that orchards and vineyards cultivated with intensive technologies have very limited space for machinery movement, making conventional tractors unsuitable. Modern horticulture and viticulture therefore require compact, energy-efficient tractors with short wheelbases, minimal width and height, small wheels, and lightweight designs to ensure easy maneuverability. The small turning radius is essential for efficient operation in narrow rows. In selecting such machinery, both size and weight are key factors, as frequent tractor movement can cause soil compaction up to 50 cm deep. To reduce this effect and maintain soil health, the use of wider tires is recommended.

Taking these factors into account, the theoretical and experimental study of the control systems of such tractors is of great importance, since they directly affect maneuverability, turning radius, and overall work efficiency in conditions of limited orchards and vineyards; similar tractor-system kinematic modeling issues have also been considered in [11].

2 MATERIALS AND METHODS

2.1 Experimental Setup

Experiments were conducted on a prototype of a tractor developed jointly with LLC "Design and Technological Center of Agricultural Machinery" and JSC "Tashkent Plant of Agricultural Machinery." The tractor is equipped with a high-clearance front axle and a side turn mechanism, designed to increase maneuverability in conditions of narrow orchards and vineyards (Fig. 4).

Figure 4: General view of the experimental tractor with increased maneuverability under conditions of narrow orchards and vineyards.

The experiments were carried out on the basis of the developed program and methodology for conducting laboratory and field tests of a model tractor for horticulture and viticulture. In this case, when conducting laboratory and field tests of vehicles, the parameters of the tractor's steering control for horticulture and viticulture were determined.

The tractor's hydraulic steering system (HSS) consists of a steering mechanism, a hydraulic steering drive (HSD), and amplifiers. The HSD of the tractor steering system must meet the requirements [5], [10]. Tests were conducted according to the State Standard (SS) R 51960 and (SS) 30752.

The hydraulic system consists of a hydraulic pump GP-32 and GP-10, a hydraulic distributor P80, a pump-doser PD-80, a working hydraulic cylinder C50, a hydraulic tank, filters, hoses, and high-pressure pipes (Fig. 5). The power component of the hydraulic drive consists of a hydraulic pump N, a pump-doser PD, and hydraulic cylinders HC1.1; HC1.2; HC2.1; HC2.2 and connecting pipelines with working fluid. The flow of the working fluid from tank B is directed by pump N to pump-doser PD, where the distributor of the pump-doser regulates the flow of the working fluid to the working organs, or to HC1.1; HC1.2, or to HC2.1; HC2.2. Switching is carried out using locking valves LV1; LV2. After releasing its energy, the working fluid flow returns to the tank. The installation scheme of diaphragm pressure sensors in hydraulic steering is shown in (Fig. 5).

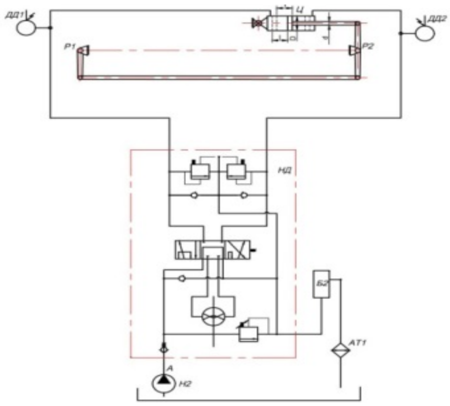


Figure 5: Diaphragm pressure sensor installation diagram in hydraulic steering.

Since the steering mechanism of the experimental tractor is actuated by a hydraulic cylinder, accurate determination of pressure variations in the hydraulic system during steering and turning is essential. For this purpose, an integrated measurement system consisting of precision pressure gauges and electronic sensors was employed.

Pressure measurements were obtained using diaphragm-type pressure sensors installed directly in the hydraulic line supplying the steering cylinder. Sensors were mounted at points ensuring minimal flow disturbance and maximum sensitivity to transient pressure fluctuations during steering maneuvers. To capture dynamic responses, the sensors were positioned both upstream of the cylinder inlet and within the return line, enabling comparative analysis of pressure distribution during left and right turning cycles. (Fig. 6 a and b).

(a) (b)

Figure 6: a) Apparatus for measuring pressure in the tractor's hydraulic system; b): SS302 model pressure sensors from SendorSensor.

The sensors were connected via shielded cables to a computer via arduino-based data acquisition system

(DAQ) with built-in 10-bit ADC. The sampling rate is up to~10 kS/s depending on configuration. MCU clock frequency: 8 MHz. (DAQ) (Fig. 7). The during testing DAQ was used to convert the signals from the modern SS302 diaphragm pressure sensor manufactured by Sendor Sensor into digital values [2], [9]. Prior to experimentation, the system was calibrated using a reference manometric standard to minimize systematic error.

Figure 7: Process of testing the pressure recording sensor by connecting it to an analogue-to-digital converter (DAQ) and a computer.

The sensors were connected via shielded cables to a computer-based data acquisition unit equipped with an arduino-based DAQ. The DAQ sampling frequency was selected to exceed the highest expected hydraulic pressure oscillation frequency, ensuring accurate recording of transient processes. Prior to experimentation, the system was calibrated using a reference manometric standard to minimize systematic error. The converter is connected to an Aspire E1-510 laptop (4), and the data transmitted from the sensor is recorded in a dedicated Arduino programme. The wiring diagram for connecting the pressure sensor to the Arduino-based DAQ is shown in Figure 8.

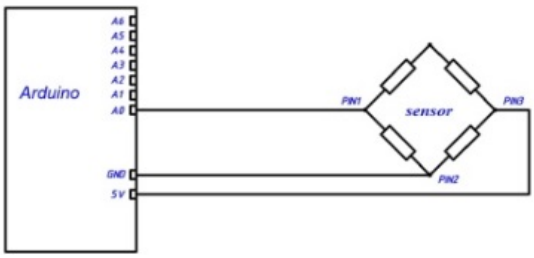


Figure 8: Wiring diagram for connecting a pressure sensor to an arduino-based DAQ.

The measurement operations are computer-controlled and, according to the functional diagram shown in Figure 9, are linked to directly in the hydraulic line supplying the steering cylinder.

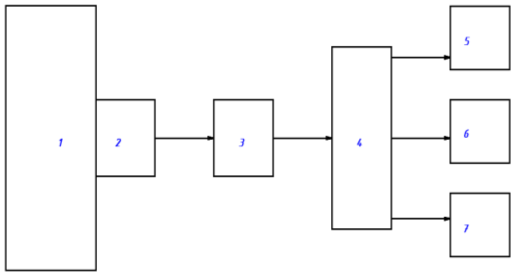


Figure 9: Functional diagram of the computerized measurement system. 1 - Tractor hydraulic system, 2 - diaphragm pressure sensor, 3 - arduino-based DAQ, 4 - computer, 5 - recording software, 6 - monitor, 7 - researcher.

Arduino is an analogue-to-digital converter based on the C/C++ programming language. It can receive data from analogue and digital sensors, transmit it to a computer and control various actuators. The measurement error is 0.2%. Pressure sensors have a measurement range of 0-40 MPa, an accuracy of 0.5%.

The calibration was performed at the LLC KTB "AVTOSOZLASH" using an IP40 piston-loaded pressure gauge accepted as a standard, which is certified by calibration certificate №. UZ-14/200-2023 dated 27 March 2023. The gauge's error is 0.5% (Fig. 10). The calibration requirements are presented in Table 1.

Table 1: The calibration requirements.

Management indicators	from	to	Note
Ambient temperature, °C	20.3	20.4	
Relative humidity of the environment, %	37.4	37.4	
Atmospheric pressure, kPa	957.6	957.8	

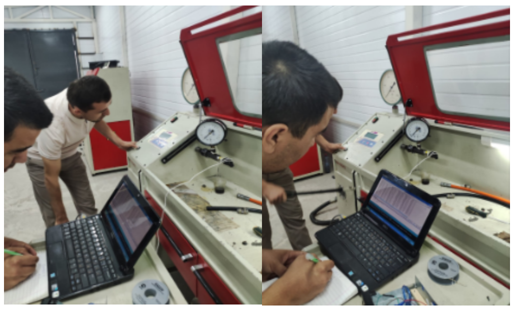


Figure 10: Process for calibrating pressure sensors with an IP40 pressure gauge.

During calibration, data from the pressure sensors and the IP40 manometer measuring instrument were obtained, and their comparative graph is shown in Figure 11.

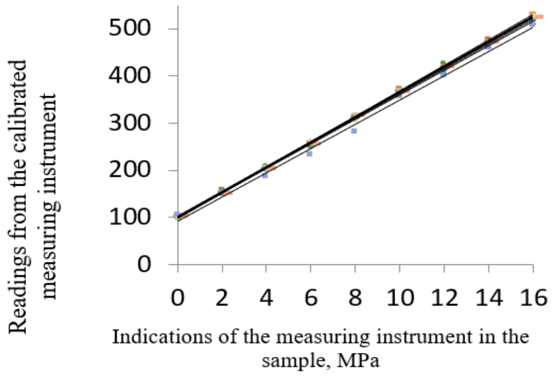


Figure 11: Comparative graph of the calibrated and sample measuring instruments.

The calibration errors amounted to 1.0-1.5%. Due to measurement and measurement errors, the maximum error was taken as 3%. In experiments, this method is effective for pressure transducers with an accuracy of 0.5% and below [2], [9].

The tests were conducted according to SS R 51960 and the Manual for the Design and Operation of Devices for Determining the Technical Condition of the KI-1097 Hydraulic System.

2.2 Methodology

Based on numerous studies dedicated to the planning, preparation, and conduct of experiments, it has been established that the correct design of experiments enables results to be achieved with the required level of precision and reliability, using a minimum number of trials. Such scientific approaches ensure the effective processing of data, the optimal and efficient use of resources, and the high scientific and practical validity of the results obtained [6], [7], [8].

The criterion for the reliability of experimental data is the general error, the components of which must be taken into account at each observation and at all stages of measurement. General error consists of measuring instrument errors and recording errors, which depend on the metrological characteristics of the measuring and recording equipment [6], [7], [8], [14].

In [6, 7, 8], the number of repetitions is determined by the standard of measurement and the specified reliability of the results.

Standard deviation is a measure of the accuracy of the arithmetic mean of a quantity measured multiple times. It is determined by the formula:

$$\sigma = \sqrt{\frac{\sum(a_i - \overline{a})^2}{n-1}}, \quad (1)$$

where a_i - measurement result; $\overline{a}$ - average arithmetic of measurements; n - number of measurements.

In experimental research, reliability is a fundamental criterion for assessing the trustworthiness and reproducibility of data. This is defined as the probability of consistent results from repeated measurements of a similar quantity under identical conditions. High reliability indicates that the measurement system and experimental procedure are stable, reproducible, and minimally influenced by random or systematic errors. The greater the relative variation of the results and the greater the reliability of the experiment, the greater the number of repetitions. This relationship is presented in Table 2 [7], [8], [9].

To select the minimum number of experiments from this table, it is necessary to set the reliability H and the error Δ, taken in standard fractions σ. In the absence of data for establishing the standard value, it is assumed [8], [10] that the marginal error is approximately equal to the highest possible statistical error, and then:

$$\Delta_n \approx \pm 3\sigma, \quad (2)$$

Table 2: Required number of experiments (measurements).

Error, Δ	Experience reliability, H						
	0,6	0,7	0,8	0,9	0,95	0.99	0,999
3,0	1	1	1	2	3	4	5
2,0	1	1	2	3	4	5	7
1,0	2	3	4	5	7	11	17
0,5	4	6	9	13	18	31	50
0,4	6	8	12	19	27	46	74
0,3	9	13	20	32	46	78	127
0,2	19	29	43	70	99	171	277
0,1	72	169	266	273	387	668	1089
0,05	285	431	659	1084	1540	2659	43387
0,01	7090	10732	16436	27171	38416	66358	108307

Reliability H for measurements related to machine design [9] is recommended to be 0.9, and for measurements of quantities that are the basis for further calculations - 0.99. Based on the data obtained from Table 1, we will determine the number of repeated experiments: - when comparing experimental studies of HSS dynamics with experimental studies, H=0.95; n=3. The main results of the experimental studies were processed according to statistical processing rules [6, 7, 8]. In this case, the following values were determined:

arithmetic mean:

$$\overline{\sigma} = \frac{x_1+x_2+x_3+\cdots+x_n}{n} = \frac{\sum_1^n x_i}{n}, \qquad (3)$$

where n - is the number of experiments; x_i- value of the i-th experiment;

dispersion:

$$\sigma^2 = \frac{\sum(x_i-\overline{x})^2}{n-1}; \qquad (4)$$

standard deviation according to the formula (1);

Variation coefficient:

$$V = \frac{\sigma}{\overline{x}}100\%; \qquad (5)$$

Possible deviation of the arithmetic mean:

$$\sigma_{\overline{x}} = \frac{\sigma}{\sqrt{n}} = \sqrt{\frac{\sigma^2}{n}}; \qquad (6)$$

Relative error in estimating the arithmetic mean in percent:

$$\sigma_{\overline{x}}\% = \frac{\sigma_{\overline{x}}}{\overline{x}}100, \qquad (7)$$

maximum deviation σ_{max}.

Based on the derived analytical expressions, the experimental data, stored in CSV files, were systematically processed and analyzed using Python to ensure accurate numerical evaluation and reproducibility of results. The data-processing procedure included automated parsing of CSV files, application of calibration coefficients, digital filtering to remove noise and outliers, computation of performance metrics, and visualization of system behavior. Graphical representations of the determined parameters were created using MATLAB and Microsoft Excel to visualize trends, compare experimental and theoretical results, and facilitate interpretation of system behavior under varying operating conditions.

3 RESULTS AND DISCUSSION

The analysis showed that the pressure parameters of the hydraulic steering system (HSS) are highly sensitive to operational conditions. In particular, substantial fluctuations were observed under different road surface types as well as at varying engine rotational speeds, indicating a strong dependence of steering hydraulics on both load and dynamic operating regimes.

The results of pressure changes in the HSS during turning, circular motion, maximum pressures depending on engine speed and test section type, and steering wheel rim forces are shown in Figures 12-14. and Tables 3 and 4 [13].

Table 3: Change in pressure p in the tractor's steering control unit.

№	Type of test site	Engine speed, min^{-1}		
		1000	1500	2200
		Maximum pressure in the hydraulic system, MPa		
1	Unpaved	9.8	10.9	12.4
2	Paved	9.3	10.1	11.6
3	Smooth surface	7.6	8.2	8.6

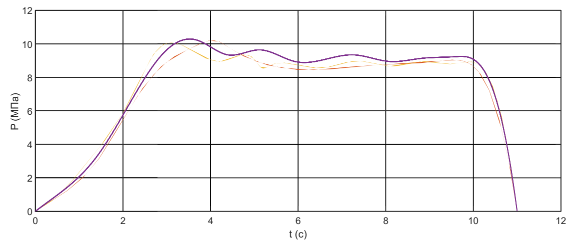
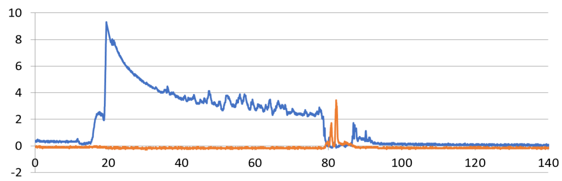


Figure 12: Pressure change in the steering control unit when the tractor turns on a dirt road.



- pressure in the cavities of the hydraulic cylinder.

Figure 13: Pressure change in the hydraulic unit during circular movement of the tractor.

Figure 14: Measuring the force on the steering wheel rim.

Table 4: Force on the steering wheel rim.

№	Type of test site	Engine speed, min-1		
		1000	1500	2200
		Force on the steering wheel rim, N		
1	Dirt	15	12	10
2	Rocky	14	11	8
3	Paved	7.8	6	5
4	Concrete	7.5	5.8	4.9

3.1 Program Code

Description of the computational results.

Statistical processing of experimental data is carried out according to the algorithm presented in the block diagram in Figure 15. The initial data is imported from the CSV file, after which the number of measurements is determined. Next, standard deviation and variation coefficients were calculated according to standard statistical methods. The obtained parameters are output in numerical form.

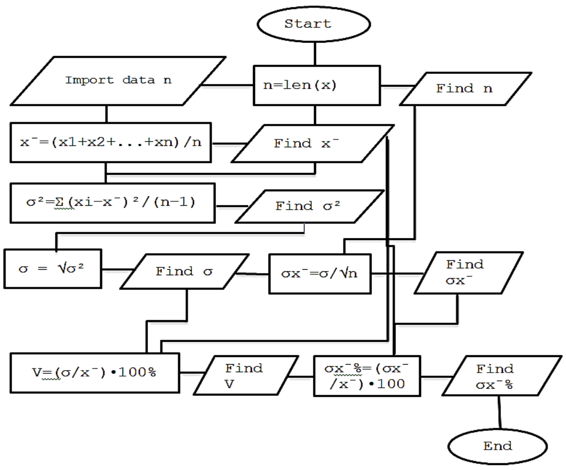


Figure 15: Block diagram of statistical processing of experimental data.

All calculations were performed using software, ensuring high computational accuracy and minimizing human error. The results provide a reliable basis for further analysis.

Graphical analysis of the experimental data shows that, after a system start-up delay of 2-4 seconds, hydraulic pressure rises sharply to approximately 10.23 MPa before stabilizing at resistance values. The maximum pressure observed was 2.8% above the mean, and the maximum coefficient of variation was 10%, indicating that results closely matched average values.

During tractor operation on a dirt road, the hydraulic steering system exhibited an average maximum pressure of 9.95 MPa, nominal pressure of 8.6 MPa, response time of 3.8 s, transition time of 5.2 s, and a pressure overshoot of 1.35 MPa. These findings confirm that the system meets the specified technical requirements.

4 CONCLUSIONS

Pressure variations in the prototype tractor's hydraulic steering system were studied during turning and reverse maneuvers under different engine speeds, surface types, and steering forces. Key operational parameters were determined: steering wheel play of 3° and rim forces ranging from 4.9 to 15 N, well within the GOST 28174-89 limit of ≤30 N.

Analysis of the pressure-time characteristics obtained during tractor turning on an unpaved road showed that the average maximum pressure in the hydraulic steering unit was 9.95 MPa, the nominal operating pressure was 8.6 MPa, the response time was 3.8 s, the transition time was 5.2 s, and the pressure overshoot reached 1.35 MPa.

The maximum pressure observed exceeded the mean by only 2.8%, and the coefficient of variation remained below 10%, indicating low variability and high repeatability of measurements. These results confirm that the hydraulic steering system's dynamic and static performance fully meets the specified technical requirements.

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