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Data Measuring System for Torque Measurement on Running Shafts Based on a Non-Contact Torsional Dynamometer

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Abstract. The need for power measurement transmitted by the running shaft has led to the need for using devices for measuring torque on the shaft. Of particular importance is the power measurement on high-speed machines, wherein some cases conventional measurement systems are either unsuitable or have low accuracy. Currently, data measuring systems are widely used in the researches of turbomachines. They allow to receive, process, transmit, store and display measurement data. Their application is relevant in relation to the priority of experimental study and subsequent modeling of characteristics and performance factors of expansion machines. The purpose of this research is a design and generation of the data measuring system for measuring torque on the running shaft of vortex expansion machines using a non-contact torsional dynamometer (strain-gauge clutch). The research has considered the results of the development of data measuring system, performed a theoretical analysis and presented the results of the practical application of the non-contact strain-gauge dynamometer designed for torque measurement on the shaft of low-power expansion machines when operating under bench test conditions. Has dealt with the problems of development, calibration.

Keywords: data measuring system, torque, coupling, resistive-strain sensor, vortex expansion machine.

1 Introduction

The necessity of power measuring transmitted by the running shaft has led to the need for usage of devices to measure the torque on the shaft. An increase of the accuracy of measuring the effective power on the shaft allows to more accurately determine the efficiency of plants, improves the quality of the experiment and thereby allows to detect an effect of unobtrusive factors on the efficiency of power plants. Of particular importance is the measurement of power in high-speed installations, where in some cases conventional measurement systems are either unsuitable or have low accuracy.

Devices designed to measure the torque can be divided into four classes according to the principle of operation: cradle dynamometers, torsional indicators, transmission dynamometers and transducers for measuring by extrinsic parameters [1–22]. Torsion dynamometers are usually inertialess instruments and perform only the measuring function, enabling to record both the time averages and ever-varying values of the engine torque during its operation in any modes [1–18].

Currently, electronic torque measuring devices that exist on the market have a number of significant drawbacks:

– the need to complicate the design of test benches or the inability of their use for existing structures of installations;

– detector designs contain stator elements (Figures 1, 2);

– large dimensions of the measurement system (Figures 1, 2);

– the inconvenience of visual control and representation of information;

– high cost.

Therefore, the development of data measuring system (DMS) for torque measurement is a pressing challenge. The data measuring system is a collection of functionally integrated measuring, computing and other supporting technologies for obtaining measuring data, its transformation, processing to perform in the required form.

Figure 1 – Torque detector TRC-10K

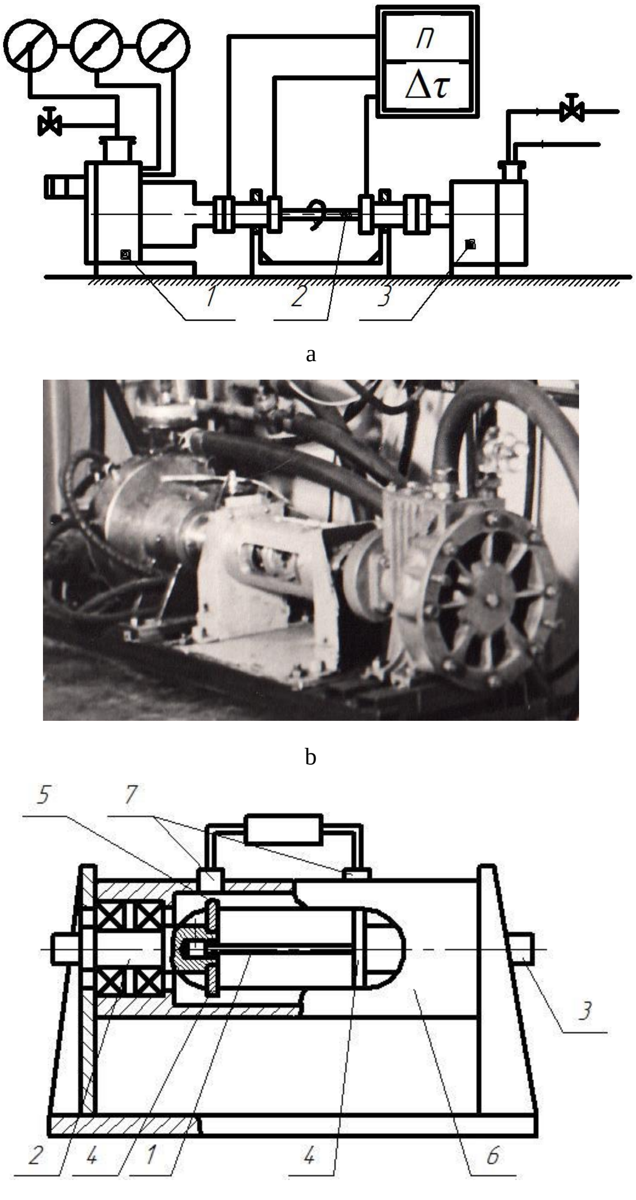
In the paper, a review is given of the results of developing the data measuring system for measuring torque on the running shaft of a vortex expansion machine using a non-contact torsional dynamometer by a wireless wi-fi connection and information processing on a computer.

2 Literature Review

Torsional dynamometers are divided into strain-gauge [3, 5–7, 10–12] and torque [4, 8, 9, 13–18]. Work process of the torsional torque dynamometer, in contrast to the torsional strain-gauge dynamometer, is based on direct or indirect measurement of a twisting angle of the torsional shaft. This angle, according to Hooke's law, is proportional to the transmitted torque.

Torsional torque dynamometers were invented much earlier than strain-gauges. They are significantly inferior to the latter in size and accuracy but are in a simple design. Torsional torque dynamometers are divided into two groups: contact and non-contact [1]. The latter has lower chatter susceptibility and greater stability of indications, as well as less demanding of maintenance. By the principle of measuring the magnitude of the twisting angle, non-contact torsional dynamometers are divided into temporary, phasic, Vernier, differential and photoelectric. In the operation [2] at the bench (Figures 2 a, b), the torque on the shaft of the vortex expansion machine 1 was measured using a non-contact torsional torque dynamometer 2, operating on a temporary basis. The load on the shaft was made by the air brake 3 (drag compressor).

Torque dynamometer (Figure 2 c) is a torsion shaft 1 of round cross-section, which is fastened at one end in the transmission shaft 2 and the output shaft 3. Disks 4 are fastened on the shafts 2 and 3 where marks are made. Shafts 2 and 3 are set up on bearings in the body structure 6, in which inductive sensors 7 are set up directly above the disks. The time interval between signals from inductive sensors is measured by a frequency meter FM3-33. This time interval is proportional to the twisting angle of the torsion shaft ψ and to the shaft torque accordingly.



a

b

c

Figure 2 – Test facility for researches of vortex turbomachines with a mean of measuring the torque on the shaft (non-contact torsional torque dynamometer): a – test facility scheme; b – photo of the test facility; c – torque measurement device

Due to the abovementioned, the purpose of the research is a generation of the data measuring system for measuring torque on the running shaft of a vortex expansion machine using a non-contact torsional dynamometer. To achieve this purpose, the following objectives have been formulated:

– generation and calibration of a strain-gauge clutch for torque measurement;

– building software for the transformation of measuring data with the purpose of providing in the required form.

3 Research Methodology

The torque on the shaft was calculated as a function of the twisting angle of the torsion shaft, N·m:

$$M = K_M \cdot (\psi - \psi'); \qquad (1)$$

where K_M – dimensionless calibration notice of dynamometer; ψ – the central angle between marks on torsion meter discs under load (deg):

$$\psi = \omega \cdot \tau \cdot 10^{-3} = 6 \cdot n \cdot \tau \cdot 10^{-3}, \qquad (2)$$

where $\omega = 6 \cdot n$, $\mathrm{deg/s}$ – rotational speed; n – revolution rate (rpm); τ – the time interval between sensor signals when operating under load (ms); ψ' – the central angle between marks on torsion meter discs at idle (no torque load) (deg):

$$\psi' = \omega \cdot \tau' \cdot 10^{-3} = 6 \cdot n \cdot \tau' \cdot 10^{-3}, \qquad (3)$$

where τ' – the time interval between sensor signals during idle operation (ms).

By torque-transmitting, the torsion shaft undergoes elastic strain and the angle ψ changes its value. The considered construction design allows one to measure conditionally instantaneous (in one revolution of the crankshaft) torque values.

But this construction design has drawbacks such as:

- sensor designs contain stator components, which leads to complication of the bench design Figure 2;
- large dimensions and complex design of the measurement system Figure 2;
- power loss in bearing frictions should be considered.

Up to date, strain-gauge instruments, the principle on which they operate is based on the dependence between the conductor stretching and its electrical resistance, are developing intensively. Due to the ever-decreasing size and progressive stability of the electronics, it is possible to design sensors with enhanced accuracy and better dynamic performance. Modern strain-gauge instruments are compact, have the highest accuracy relating to other types of dynamometers designed for torque measurement, and can also be placed directly on a running shaft, without requiring the installation of additional means between the engine and the load.

Measurement using resistive-strain sensor is based on the change in its resistance under external actions. In mechanics, the resistance of the resistive-strain sensors is changed due to its deformation, which results under the operating force.

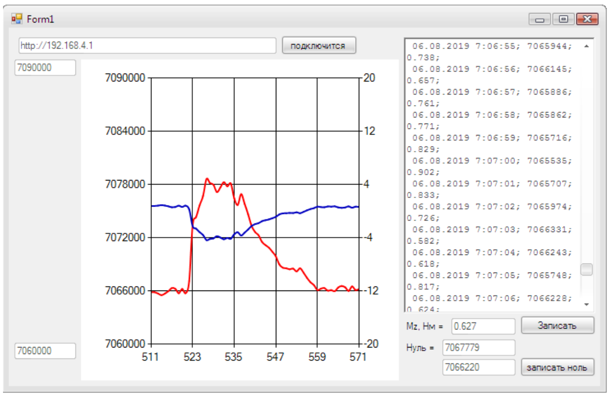
It is known that during torsion, individual shaft elements undergo pure shear deformation and the main strain runs on the platform inclined at an angle of 45° to the shaft axis. Therefore, the resistive-strain sensors are located at the intersection of the main area with the shaft surface, i. e., along a helical curve forming an angle of 45° with the shaft axis.

Using modern advances in the field of strain-gauge instruments and means of transmission facilities it is proposed for measuring the torque on the shaft of the expansion turbomachine, to create data measuring system, which includes a strain-gauge clutch, replacing two clutches and a torque measurement device on the bench shown in Figure 2 (see Figure 3).

Figure 3 – Turbogenerator based on a vortex expansion machine with a strain-gauge coupling

4 Results

To determine and record the torque value, a device (strain-gauge coupling) has been developed, which consists of a torque pin and placed in it resistive-strain gages, boost, wi_fi transmitter and battery. To register fast-changing processes, processing of measured data, upkeeping safe storage of the received information, providing measurement results in a tabular and graphical form, software in C# programming language for the Windows operating system was created (Fig. 4) The use of own software allows to configure the visualization and data storage in a convenient form for the researcher and allows to easily integrate this coupling in the data measurement system of the bench.



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0.817;
 06.08.2019 7:07:06; 7066228;
0.624;
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Mz, Нм = 0.627

Нуль = 7067779

7066220

Figure 4 – Software interface

Based on the above-mentioned technical means, a data measurement system for torque measurement has been created, block diagram/structural chart of which is shown in Figure 5.

Strain-gauge clutch for torque measurement is shown in Figure 6.

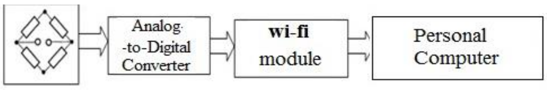


Figure 5 – Block diagram of the data measuring system for torque measurement.

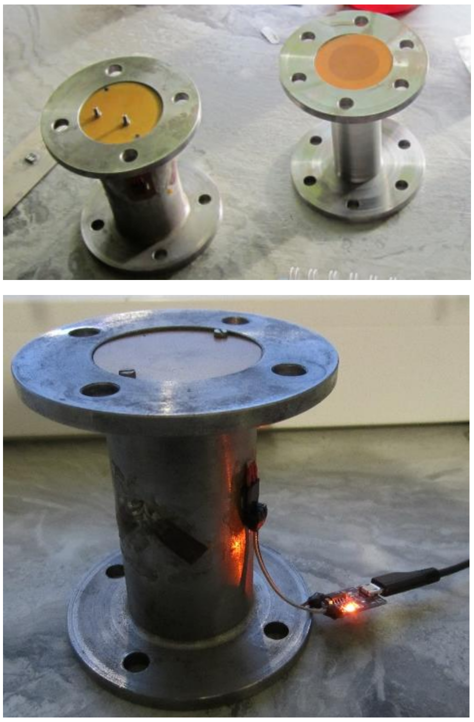


Figure 6 – Strain-gauge clutch for torque measurement

It is known that during torque measuring an output signal (voltage) from strain gauges, connected by complete bridge connection is an analog with a low value (within a few mV). For this reason, to register this signal with electronic devices a boost is required (Fig.5) which increases the measured voltage in the possible registered range of the receiving device. To amplify the signal and transform the analog signal to digital, an HX711 ADC (analog-to-digital converter) strain booster is used. ESP8266 ESP-01 wi-fi module is used as a wireless signal transmission from the bridge of the resistive-strain sensor. Digital signal from the HX711 ADC is transmitted to the transmitter thereafter it is transmitted to the environment to the receiving apparatus (phone or PC). This scheme compared to the frequently used [3–6, 10] provides a number of advantages: usability, affordability at a good transmission quality, ease of use, no need for receiving apparatus production since modern PCs allow to receive wi-fi signal.

The received signal is processing, recording and visualizing by the generated software. The power supply of the circuitry is provided by a 18650 Li-Ion lithium battery.

Mass-dimensional characteristics of the coupling are practically the same as those of standard couplings for torque transmission. Installation of electronic components on the axis of rotation inside the coupling allows avoiding the occurrence of significant centrifugal loads on the scheme elements when operating at high speeds of the turbomachine rotor.

The torsion shaft of the coupling has a bearing length of 100 mm, an internal diameter of 32 mm or 40 mm (Figure 6). The wall thickness is selected considering the range of torque variation and ranges from 0.5 mm to 5.0 mm. Measuring a range of the dynamometer: $M = –100–100$ N·m, $n = 100–10000$ rpm; allowable load limit 200 N·m.

Calibration of the created strain-gauge coupling was performed. Calibration allows not only to establish a connection between the indicator of the recording system and the value of the measurand but also to check the system operation in the range of variation of the input magnitude.

Calibration researches were done at room temperature (from 0 to 25 °C) as follows: known beforehand values of the measurand, for example, torque on the shaft is fed to the input of the measuring system, and at the output record the system indicators on these impacts. The torque on the shaft is created by the application of a load of known weight on a measuring beam with a length of 1 m, fixedly connected to the shaft (Figure 7). Measurement error ±0.25 N·m.

As a result, the dependence between the torque and instrument readings (calibration curve) was obtained, as well as the equation of this dependence. Torque changing which recorded the device during the calibration process is shown in Figures 8 and 9 is a calibration curve.

Figure 7 – Calibration of the instrument for torque measurement

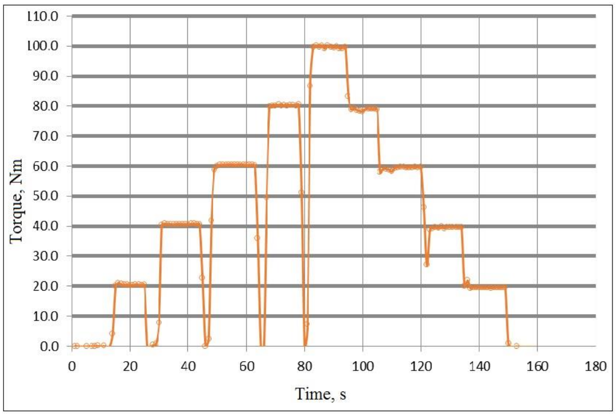


Figure 8 – Torque changing during the calibration process

The dependence of instrument readings on torque is determined by the following equation:

$$M = a \cdot p + b \tag{4}$$

where p – instrument readings; a, b – factors that are determined during calibration for each coupling design Figure 6.

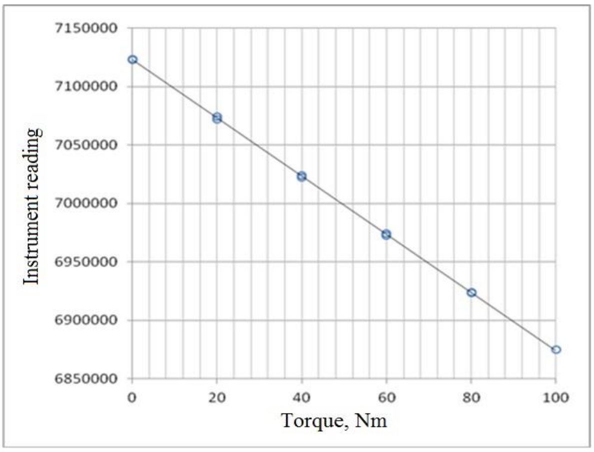


Figure 9 – Calibrated curve

The device was tested in dynamics at the testing facility of low-power turbomachines of the department of Technical Thermal physics of Sumy State University as a part of turbine-generators based on jet-propelled expansion machine (Figure 10) and vortex expansion machine (Figure 3). During the dynamic check, the instrument measured the torque at a variable frequency of rotor spinning from 500 to 10000 rpm.

Fig. 10 – Instrument's dynamic checks for torque measurement

The table shows the main technical characteristics of the developed strain-gauge coupling and TRC-10K clutch (Figure 1).

Table 1 – The main technical characteristics of the strain-gauge coupling

Technical characteristics	Strain-gauge coupling 100	TRC-10K
Torque range, N·m	–100–100	–100–100
Measurement error (including nonlinearities), N·m	±0.25	–
Transmission of an output signal	wi-fi	cable
Permissible maximum rotation frequency of the shaft, rpm	10 000	10 000
Temperature conditions (calibrated), °C	0–30	0–30
Dimensions (L×D), mm	100×90	240×115
Weight, kg	1.0	8.0

On Figures 11 and 12, torque changing, which registered the device during the checks of the vortex expansion machine of Figure 3 at a speed of 2500–3000 rpm is shown.

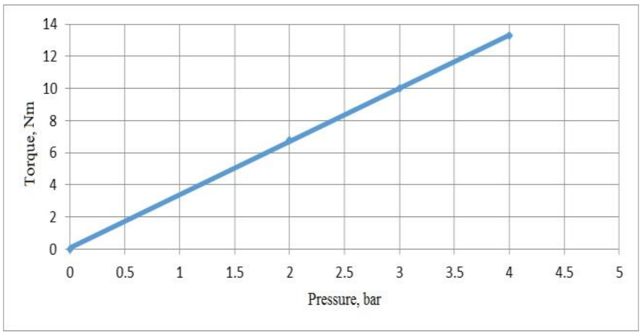
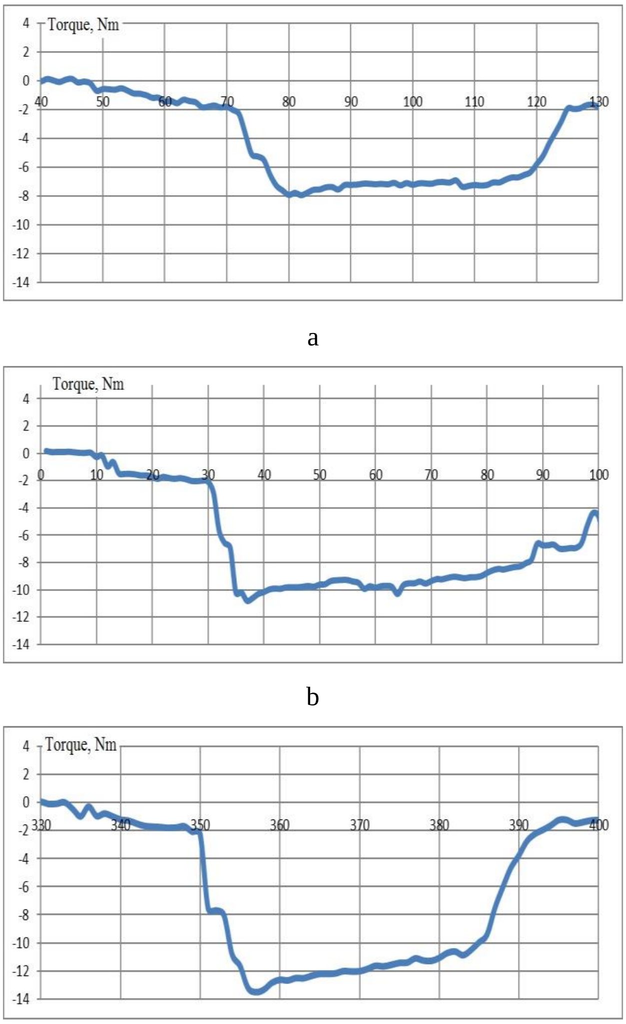


Figure 11 – The dependence of the torque on the shaft of the vortex expansion machine (Figure 3) on the overpressure at the input



a

b

c

Figure 12 – Torque changing during operation of the vortex expansion machine on the bench (Figure 3) with input pressure 2 bar (a), 3 bar (b), and 4 bar (c)

5 Conclusions

A strain gauge coupling was developed to measure the torque on the shaft of the expansion machine, that made it possible to determine the machine shaft power and its efficiency. Mass-dimensional characteristics of the coupling are practically the same as those of standard couplings for torque transmission. The developed clutch can operate at high rotational frequencies of the rotor of the turbomachine. The coupling meets the requirements for measurement error, measurement range and, if possible, for working with other sensors during testing.

Own software that configures the visualization and data storage in a convenient form for the researcher and allows to easily integrate this coupling in the data measurement system of the bench was generated.

Based on the strain-gauge coupling and software, data measuring system has been created, which, in comparison with known ones, has a compact and easy-to-work design with a minimum number of elements. Developed data measuring system allows measuring the torque on the running shafts in a non-contact way without requiring complication of bench design with the required accuracy.

Findings of experimental researches confirm the reliability of the developed data measuring system under static and dynamic load.

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УДК 621

Інформаційно-вимірювальна система для вимірювання обертального моменту на валах, що обертаються, на основі безконтактного торсіонного динамометра

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Анотація. Необхідність вимірювання потужності, переданої валом, що обертається, призвела до важливості застосовування пристроїв для вимірювання обертального моменту на валу. При цьому, особливого значення набуває вимірювання потужності на високошвидкісних установках, де у більшості випадків традиційні системи вимірювання або непридатні, або мають недостатню точність. У даний час при дослідженнях турбомашин широко розповсюджені інформаційно-вимірювальні системи. Вони дозволяють отримувати, обробляти, передавати, запам’ятовувати і відображати вимірювальну інформацію. Їх застосування актуальне у зв’язку із пріоритетністю експериментального вивчення і подальшого моделювання характеристик та показників ефективності розширювальних машин. Метою даної роботи є розроблення і створення інформаційно-вимірювальної системи для вимірювання обертального моменту на валу розширювальних машин, що обертається з великою швидкістю, за допомогою безконтактного торсіонного динамометра (тензометричної муфти). У роботі наведені результати розроблення інформаційно-вимірювальної системи, виконаний теоретичний аналіз і результати практичного застосування безконтактного тензометричного динамометра, призначеного для вимірювання обертального моменту на валу розширювальних машин малої потужності за умов стендових випробувань. Додатково розглянуто питання проектування, тарування і застосування спроектованого динамометра.

Ключові слова: інформаційно-вимірювальна система, обертальний момент, динамометр, тензорезистор, вихрова розширювальна машина.