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# Determination of the Force Acting on the Gas Turbine Wing in the Heat-and-Power Installations

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**Abstract.** A design scheme for measuring the short-term impulse force acting on the gas turbine wing using the induction method was developed. It was compared with the results measuring the same force using the thermal method. The results of the impulsive force measurement by induction and thermal methods were also compared. After considering the experimental conditions, the thermal method was chosen for experimental studies. It allowed experiments to be conducted with intervals to ensure temperatures of the same magnitude on the surface of the flue gas on the gas turbine wing. The proposed measurement scheme using the induction method was also applied to control and manage the optimal conditions of the gas turbine power-generating device. As a result, a theoretical relationship was obtained as a mathematical relationship between the signal received during the measurement by the induction method and the force to be measured. The conditions for determining the actual value of the force were developed. The error in determining the force acting on the gas turbine wing using the induction method did not exceed 3 %.

**Keywords:** power generation, process innovation, gas turbine device, rotor, induction sensor.

## 1 Introduction

Determination forces acting on gas turbine wings is a challenging problem in designing heat-and-power installations [1, 2].

The proposed electric power-generating gas turbine device can be a component of a completely original type of thermal power plant [3, 4]. It works as the primary source of natural gas [5].

A flue gas flow is formed by igniting the mixture of natural gas and air accumulated in one of its main constituent elements, the so-called combustion cell [6]. It is directed towards the wing of the gas turbine, and the magnitude of the generated electrical energy depends on the force $F$ generated by its operation because of the retarding electromagnetic force $F_{em}$ in the rotor winding of the generator and included in the device to overcome employing the latter [7, 8].

In particular, the conductor of length $l$ of the magnetic induction $B$ and the rotor of the generator rotating at the velocity through which the current $I$ passes is influenced by the retarding electromagnetic force $F_{em}$, which is calculated by the formula:

$$F_{em} = BIl. \tag{1}$$

The induction vector $\vec{B}$ is perpendicular to the conductor $l$. That is, the magnitude of the retarding force of the rotor depends on the magnitude of the electricity generated by the generator.

The force $F_{mech}$ acting on the blades of the gas turbine by the flue gas flow from the combustion chamber acts opposite to the force $F_{em}$.

At nominal operation of the generator, the following condition should be satisfied:

$$F \geq F_{em}. \tag{2}$$

## 2 Literature Review

When developing the design, technology, and control method [9] of a heat-and-power installation, as well as during its operation, the main criterion for evaluation and control of the ongoing thermal and aerodynamic processes [10] was the force $F$ acting on the air turbine wing, and obtaining its maximum possible value was the main aim of our research [11].

Determining its magnitude is necessary for studying these processes through experimentation or modeling. However, it is not an easy task, as the duration of combustion of the mixture of natural gas with air accumulated in the cell and, accordingly, the duration of the action of force $F$ on the air turbine wing is less than 1 second, which makes it impossible to use all kinds of standard, proper measuring devices.

According to the pressure $P$ measured in the combustion cell of the gas turbine device, if the area of action $S_{gt}$ of the combustion gas ejected from the cell on the wing of the gas turbine device is known, then it will be possible to determine the force acting on the wing:

$$P = \frac{F}{S_{gt}}. \tag{3}$$

The research was suggested to address this problem. In particular, indirect methods of determining this force are proposed, such as the so-called study of thermal and induction methods.

The so-called thermal method for indirectly determining force $F$ is as follows. First, the temperature of the flue gas coming out of the combustion cell and the temperature inside the combustion cell depends on the percentage content of the fuel gas and air mixture [12].

Second, the latter also determines the force of the flue gas flow generated on the gas turbine wing and the temperature of the area of action [13].

Finally, the temperature of the gas turbine wing, measured on the flue gas action surface, should be correlated with the magnitude of the abovementioned force.

Due to the short duration (about 1 ms) of the force $F$, it cannot be measured either by a mechanical, for example, membrane, impact manometer, or by pressure measuring devices acting on piezo elements due to their inertia.

In the induction devices used for measuring non-electric quantities, including mechanical force, the electromagnet located in the coil is moved under the influence of the mechanical quantities to be measured, which is correlated with the magnitude of the electromotive force induced at that time. It is difficult to separate the electromotive force induced in the coil and its corresponding current from the disturbing signals operating at that time by the action of the impulsive force with a duration of about 1 ms on the electromagnet. It is related to the inertia of the measuring mechanisms, which also affects the accuracy of the measurement.

Various methods of measuring the temperature in metal melting and at the metal interface in experiments, including pyrometers and their calibration, were deeply discussed in [13, 14]. Based on the analysis of these materials, it was decided to investigate this method for measuring the temperature of the gas turbine wing in places affected by the flue gas flow coming from the combustion chamber.

The papers [15, 16] analyzed the thermophysical properties of electro-slag remelting and the issues of electrode melting during electro-slag remelting.

The papers [9–13, 17] presented studies on modeling and controlling the thermal processes during the electro-slag remelting of metals.

The papers [18, 19] discussed the principles of operation, modeling, designing, and controlling electrical machines according to magnetic induction. The principles of induction applied at that time formed the basis for producing a highly sensitive inductive sensor and its use for measuring short-duration, large-magnitude impulses (about 1 ms).

Factors affecting the efficiency of thermal gas turbine devices were discussed in the research works [20, 21]. As a result, controlling and managing the gas turbine device was proposed.

## 3 Research Methodology

The temperature in the center of the flue gas action on the wing was measured using a laser pyrometer [14]. During all tests, the distance between the combustion cell and the measuring surface was maintained, as well as the location of the pyrometer, which was the angle of inclination, the same location as the measuring point related to the measuring surface (Figure 1).

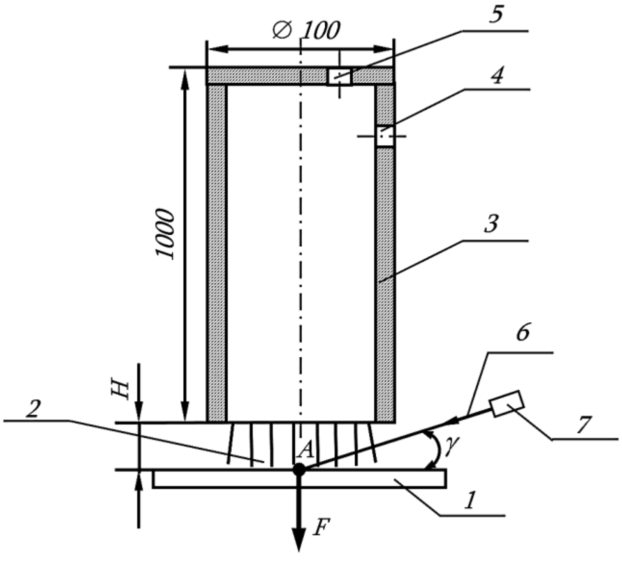

Figure 1 – The design scheme for measuring temperature on the gas turbine wing surface: 1 – gas turbine wing; 2 – flue gas flow; 3 – combustion cell; 4 – gas-air mixture supply valve; 5 – spark ignition valve; 6 – laser beam; 7 – pyrometer; A – measurement point; $\gamma$ – bean inclination angle

At the same time, when starting the measurement, the ambient temperature on the wing surface was always maintained, which was achieved by maintaining an appropriate interval between measurements.

Measurements were conducted in the combustion cell during the generation of flue gas flow at different percentages of the propane-air mixture.

The tests were conducted in a cylindrical combustion cell with a bottom on one side, 100 mm in diameter and 1000 mm in length (Figure 2).

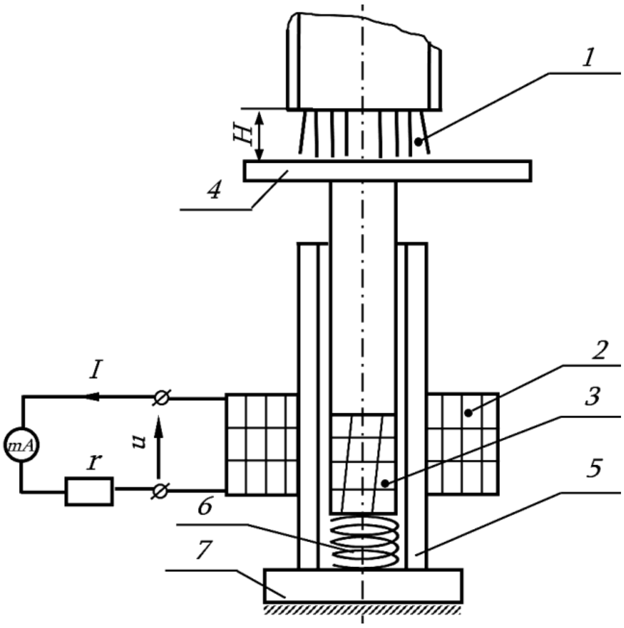

Figure 2 – The design scheme of the induction device: 1 – flue gas flow; 2 – induction coil; 3 – permanent magnet; 4 – gas turbine wing; 5 – sensor case; 6 – spring; 7 – sensor's bottom

A mixture of natural gas and air of different contents was supplied from a valve near the bottom.

The spark supply device was also installed at the bottom of the combustion cell.

Figure 3 illustrates the implementation scheme of the induction approach for experimental measurements of force *F*.

The force was measured using the induction devices as follows. The flue gas flow emitted from the combustion cell moved the magnet toward the electromagnetic coil by acting on the wing at a distance of *H* from it.

As a result, due to the change in the magnetic flux penetrating the coil, the induced electromotive force or the magnitude of the current due to the latter was measured using a digital ammeter.

The more significant the force *F* acting on the wing, the greater the rate of change of the magnetic flux created by a permanent magnet, and the greater the induced electromotive force and the current it provides [22].

The distinguishing feature of the proposed induction method is that the induction sensor is made on a permanent magnet, and the permanent magnet moves in the induction coil.

In addition, before the measurement, the permanent magnet occupies such a position relative to the induction coil that ensures the maximum speed of change of the magnetic flux of the induction coil during the measurement process. This increases the sensitivity of the induction sensor. The proposed device uses this sensor to measure the large impulse force (Figure 2).

At different percentages of a mixture of natural gas and air, the values of the current measured during the action of the generated flue gas flow on the wing are also presented in Table 1.

During each experiment, it was necessary to maintain the same value of *H* between the combustion cell and the wing.

It should be noted that actually, the surface of the gas turbine wing has a complex configuration but is based on the objective of developing a method of experimental determination of the acting force as a result of the comparison with each other during the impulsive load on the gas turbine wing, in particular, to compare thermal or inductive sensors, to select the best one, we consider it sufficient that the surface of the gas turbine wing should be a plane perpendicular to flue gas flow.

In all eight tests within the experiment, the natural gas content in the mixture supplied to the combustion cell varied from 5 % to 12 %, with an interval of 1 %. Each experiment was repeated three times.

## 4 Results

Table 1 presents the data from the experiment.

Figures 3, 4 illustrate the experimental relationship between the so-called field of the measured values built according to this field.

Table 1 – The result of measuring the temperature on the gas turbine wing and the electromotive force induced by the inductive sensor and calculating the correlation coefficient

| No. | Natural gas content $Y$, % | Gas turbine wing temperature $X_1$, °C | The reading of the inductive sensor $X_2$, mA | Correlation coefficient $r_{Y,X1}$ | Correlation coefficient $r_{Y,X2}$ |
|---|---|---|---|---|---|
| 1 | 5 | 43 | 23 | 0.97 | 0.98 |
| 2 | 6 | 46 | 25 | | |
| 3 | 7 | 45 | 28 | | |
| 4 | 8 | 48 | 30 | | |
| 5 | 9 | 50 | 32 | | |
| 6 | 10 | 52 | 34 | | |
| 7 | 11 | 54 | 36 | | |
| 8 | 12 | 57 | 38 | | |

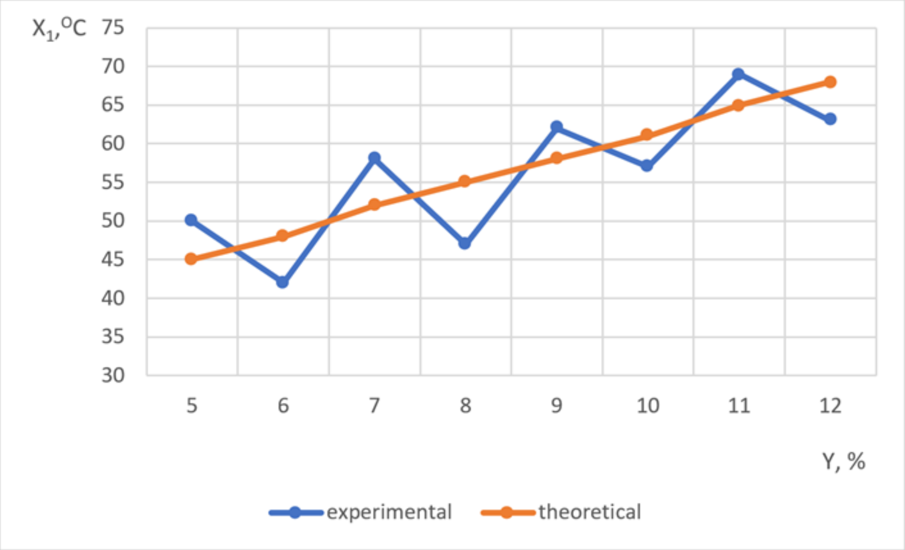

Figure 3 – Dependence between the gas turbine wing temperature $X_1$ and fuel mixture composition $Y$

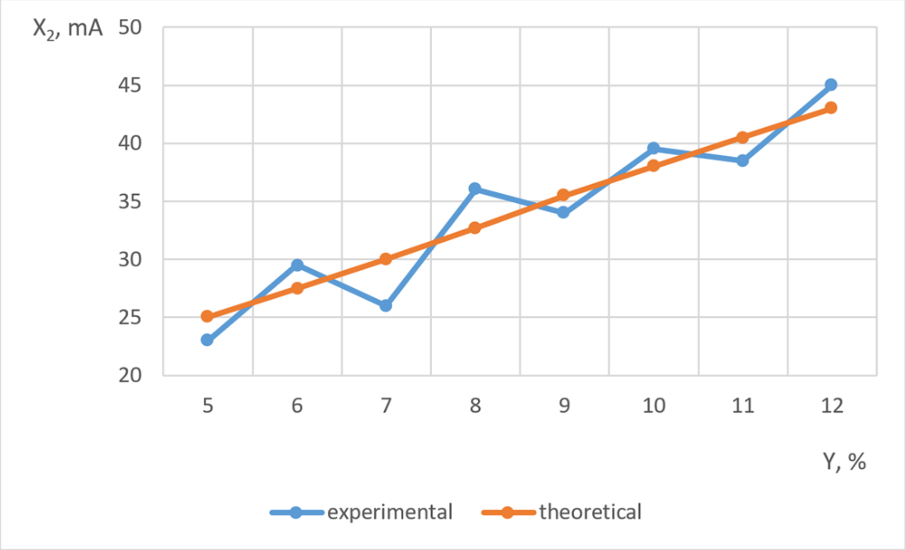

Figure 4 – Dependence between the current $X_2$ measured by the inductive sensor fuel mixture composition $Y$

The relationship between the temperature measured on the surface of the gas air turbine blade and the content of the mixture of natural gas and the air is linear.

The value of the correlation coefficient can be used to evaluate the relationship between them, and for the further study of this relationship, the regression analysis [23] can be applied.

Also, to evaluate the influence of the natural gas content in the air, the magnitude of the electromotive force induced in the induction coil on the gas turbine wing and the current due to the latter can also be evaluated by the correlation coefficient between them. Calculations showed that in both cases, the correlation coefficients are high $r_{Y,X1} = 0.97$, and $r_{Y,X2} = 0.98$. These values indicate that the linearity of the mentioned graphical dependencies was justified.

However, due to the heat transfer during the measurements, as shown by our additional studies, it is necessary to maintain a significant interval between the measurements, which is necessary to ensure that the measurement surface has the same initial temperature (ambient temperature) before each measurement. This can be done under conditions of experiments in individual tests, but it is unacceptable in the case of the need to control and manage the processes occurring in the combustion cell [24].

Due to the above circumstance, the inductive method should be preferred despite the high correlation between the two measurement methods. Here, it is only necessary to maintain a constant value of $H$ between the combustion cell and the surface of the gas turbine blade (Figure 2), which is easy to perform and does not require additional measures.

In addition to the above, using the inductive method makes it easier to determine the actual value of the force acting on the gas turbine blade caused by the flue gas flow. For this purpose, it is necessary to repeat the experiment with the given specific content of the mixture of natural gas and air and select a mass load dropped from a distance of $H = 1$ m from the wing surface, which causes the induction transformer to receive the electromotive force with the same magnitude and the corresponding current, as would be caused by the action of the presented flue gas flow. Thus, multiplying the mass of the selected load by the acceleration of free fall will give us the weight of the mass of the selected load, which can be considered practically equal to the force acting on the wing [21].

Table 2 presents the actual value of the force acting on the gas turbine wing determined in this way.

Table 2 – The relationship between the reading of the inductive sensor and the actual value of the force acting on the wing

| No. | Natural gas content *Y*, % | Average current $\bar{X}$, mA | The experimental value of the force acting on the wing, *Y* | $X{\cdot}Y$ | $X^2$ | $Y^2$ | Correlation coefficient | Theoretical dependence |
|---|---|---|---|---|---|---|---|---|
| 1 | 5 | 23 | 5.3 | 121.9 | 529 | 28.09 | 0.97 | $Y = -1.15 + 0.3{\cdot}X$ |
| 2 | 6 | 25 | 6.6 | 165.0 | 625 | 43.56 | | |
| 3 | 7 | 28 | 7.2 | 201.6 | 784 | 51.84 | | |
| 4 | 8 | 30 | 8.0 | 240.0 | 900 | 64.00 | | |
| 5 | 9 | 32 | 8.7 | 278.0 | 1.02 | 75.69 | | |
| 6 | 10 | 34 | 9.1 | 309.4 | 1156 | 82.80 | | |
| 7 | 11 | 36 | 9.5 | 342.0 | 1296 | 90.25 | | |
| 8 | 12 | 38 | 10.2 | 387.6 | 1444 | 104.04 | | |
| | Σ: | 246 | 64.6 | 2045.9 | 7758 | 540.27 | | |

The table presents the quantities required to calculate the dependence coefficients. Considering the experimental data, we assumed that the dependence to be found has the form of a line:

$$Y = \alpha + \beta\bar{X}. \tag{4}$$

Each test was repeated three times, and to determine the coefficients of the dependence (4), their average values $\bar{X}_i$ were used.

The cargo dropped from 1 m was placed in a polyethylene bag. By this, the action of the flue gas flow on the wing was simulated approximately, and the procedure for selecting the required load was simplified.

The coefficient $\beta$ of the expression (4) is as follows:

$$\beta = \frac{m\sum_{i=1}^{m}\bar{X}_iY_i - \sum_{i=1}^{m}\bar{X}_i\cdot\sum_{i=1}^{m}\bar{Y}}{m\sum_{i=1}^{m}\bar{X}_i^2 - (\sum_{i=1}^{m}\bar{X}_i)^2} = \frac{8\cdot 204.59 - 246\cdot 64.6}{8\cdot 7758 - 246^2} = 0.3. \tag{5}$$

where $m$ – the number of tests during the experiment.

The correlation coefficient is as follows:

$$r = \beta\sqrt{\frac{m\sum_{i=1}^{m}\bar{X}_i^2 - (\sum_{i=1}^{m}\bar{X}_i)^2}{m\sum_{i=1}^{m}\bar{X}_i^2 - (\sum_{i=1}^{m}\bar{Y}_i)^2}} = 0.307\cdot\sqrt{\frac{8\cdot 7758 - 246^2}{8\cdot 540.27 - 64.6^2}} = 0.97. \tag{6}$$

An absolute term $\alpha$ in the expression (4) is as follows:

$$\alpha = \frac{\sum_{i=1}^{m}Y_i - \beta\sum_{i=1}^{m}X_i}{m} = \frac{64.6 - 0.307\cdot 246}{8} = -1.15. \tag{7}$$

That is, the expression (4) takes the following form:

$$Y = -1.15 + 0.3\bar{X}. \tag{8}$$

After inserting the actual value of the measured force *F* and the inductive sensor current, the following formula can be obtained:

$$F = -1.15 + 0.3I. \tag{9}$$

Table 3 presents the results and data of the error evaluation in determining the value of force *F*.

Table 3 – The error of the force acting on the wing, determined by the measurements on the inductive sensor current

| No. | Inductive sensor current *I*, mA | Calculated values of the force acting on the wing, N | Actual values of the force acting on the wing, N | Absolute error $\xi_i$, N | Relative error $\varepsilon_i$, N | Theoretical dependence |
|---|---|---|---|---|---|---|
| 1 | 23 | 5.75 | 5.3 | 0.45 | 8.4 | $F = -1.15 + 0.3\,I$ |
| 2 | 25 | 6.35 | 6.6 | 0.25 | 3.7 | |
| 3 | 28 | 7.25 | 7.2 | 0.05 | 0.7 | |
| 4 | 30 | 7.85 | 8.0 | 0.15 | 1.8 | |
| 5 | 32 | 8.45 | 8.7 | 0.25 | 2.8 | |
| 6 | 34 | 9.05 | 9.1 | 0.04 | 0.4 | |
| 7 | 36 | 9.65 | 9.5 | 0.15 | 1.5 | |
| 8 | 38 | 10.25 | 10.2 | 0.03 | 0.3 | |

## 5 Discussion

By expression (6), according to the inductive sensor *I*, it is possible to determine the actual value of the force acting on the gas turbine wing [25, 26].

The following values can also be calculated [27]:

– the *i*-th absolute error:

$$\xi_i = |F_i - (F_{calc})_i|; \tag{10}$$

– the *i*-th relative error:

$$\varepsilon_i = \frac{\xi_i}{F_i} \cdot 100\ \%; \tag{11}$$

– an average relative error:

$$\varepsilon_i = \frac{1}{n}\sum \varepsilon_i = 3\ \%, \tag{12}$$

where $F_i$ – the actual value of the force caused by the flue gas flow on the gas turbine blade, determined by the induction method; $(F_{calc})_i$ – the value of the calculated force acting on the wing obtained by the expression (6).

As can be seen from Figure 3, the error of determining the force acting on the wing of the gas turbine with the inductive sensor does not exceed the error limit of the measuring device, which is an indicator that the magnitude of the force acting on the wing can be determined by the expression (6) obtained according to the reading of the inductive sensor of the proposed scheme.

## 6 Conclusions

The force acting on the gas turbine wing in the form of pulses of short duration (less than 1 ms) can be measured indirectly using a laser pyrometer only in experimental studies when it is possible to maintain the necessary interval between the moments of temperature measurement. This is because the initial temperature of the wing at the moment of measurement and the interval between measurements affect the measurement result.

The inductive sensor can accurately measure the short-duration impulse force on the gas turbine wing. This is because the forces acting on the latter, including the combustion chamber, can easily be kept constant at a distance from the measuring surface of the gas turbine wing.

The results have shown that the average relative error of measuring the force acting on the gas turbine wing in small pulses using the inductive sensor does not exceed 3 %.

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