Rapid gas temperature measurement device for gas turbine engines with detection of pre-surge phenomena

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Abstract. A differential system for measurement of gas temperature in gas turbine engines (GTE) using acoustic multi-vibrators was presented. Application of acoustic multi-vibrators improves the response time by three orders of magnitude compared to thermocouples. Combined use with a gas flow meter and a vibration sensor makes it possible to measure the low-frequency component of acoustic vibrations of flowing gases in a GTE’s combustion chamber. As an example, a calculation to determine the resonance frequency of a combustion chamber of a GTE was given.

1. Introduction

Modern gas turbine engines (GTE), also used as a drive for a gas compressor unit, are distinguished by a variety of physical processes occurring in them and are complex nonlinear control objects. One of the key informative and controllable parameters characterizing the operating mode of a GTE, especially in transient modes, is the gas temperature behind the turbine. For optimal fuel consumption, the error in the measurement range from 500 K to 2500 K should not exceed 10 K at steady-state operating conditions. At present, gas temperature measurement in a GTE is most often carried out using thermocouples and thermistors, the best samples of which have inertia of the order of 3 s. In transient modes, a dynamic error arises, leading to a "overshoot" of temperature by more than 50 K. The existing methods and schemes for compensating the inertia of measuring instruments, including those with self-tuning algorithms, have low noise immunity caused by the need to differentiate the signal not only at the output of the measuring instrument, but also at the output of the model used in the self-tuning circuit. The rate of change in the gas temperature in transient modes can reach 500 K/s. The value of the non-uniformity of the temperature field of the gas turbine engine, both in front of the turbine and behind the turbine along the radius and circumference [1] is 373 K ÷ 573 K, varies depending on the operating mode of the engine.

At present, there are no direct and rapid methods for measuring the temperature of gas turbine engines, which make it possible to create GTE control systems for operation near functional, strength and temperature limitations with preventing the engine operating parameters from going beyond the permissible values.

The most common form of gas dynamic instability is surge. During the surge, periodic fluctuations in pressure and flow rate of air [2] or the fuel mixture in the longitudinal direction occur, characterized...
by low frequency and large amplitude. According to tests on stands, surge develops in a time of about 0.2 s. Almost all existing algorithms for protecting an axial compressor from surge [3] are designed not to prevent the occurrence of instability in the compressor, but to eliminate and reduce the harmful effects of an already started surge. Despite the progress achieved in the study of this phenomenon, the development of methods for detecting and measures to prevent surge in GTEs remains relevant. The development of systems for dynamic measurements of temperature and gas flow rates of GTEs will eliminate this gap.

2. Rapid gas temperature measurement device for gas turbine engines

The proposed differential system for gas temperature measurement (Fig. 1) was tested in the JSC Omsk Machine-Building Design Bureau and showed rapidness, allowing to measure instant changes in the gas temperature at control points.

Differential gas temperature measurement system for gas-turbine engines [4] consists of two channels of measuring 1 and 2 for realization differential scheme and information processing unit 3. Every channel of measurement, for example 1, consists of a jet generator 4, a piezoelectric transducer 5, an electronically tunable filter 6, a phase comparator 7, a key 8, a single vibrator 10, an inverter 11, a type of sensor selector 12, a voltage-code transducer 13.

The system works as follows. Placing jet generator 4 into a gas flow which measures absolute temperature θ, acoustic vibrations with frequencies nf are excited, which transformed with the help of piezoelectric transducer 5 into relevant electric vibrations. Then, these electric vibrations proceed into first entrance of phase comparator 7 from the first entrance of electronically tunable filter 6. The exit of phase comparator via the key 8 and first entrance of a sawtooth voltage generator 9 controls the sweep time of a linearly varying voltage. Comparator via key 8 determines voltages U1 from exit of inverter 11, which incoming in information processing unit 3 and voltage-code transducer 13, which forms code N1 proportional to the measuring temperature θ.

Information processing unit 3 implements differential measurement principle, and calculates difference of codes ∆N=N1-N2, which is proportional to temperature of gases flow.

Surge phenomena lead to failure of compressor blades, overheating of turbine blades, low-frequency vibration, axial displacement of the rotor, failure of supports and seals and, as a result, to dynamic stresses that are many times higher than the stresses for which the GTE design was designed.

The physical properties of the self-oscillating aerothermoacoustics of the GTE are synthesized in its amplitude-frequency characteristic (AFC). Therefore, establishing a relationship between the design,
the size and shape of its elements and the frequency response is of great practical importance, since it is associated with resonant destruction when a surge occurs.

Consequently, when creating a perfect GTE, it is necessary to design the engine so that the self-oscillating aerothermoacoustic process of fuel combustion is optimal, which is possible [5] in the presence of an adequate mathematical model of the self-oscillating aerothermoacoustic system of the GTE.

Vibrations of the chamber sections occur due to fluctuations in gas pressure. The reasons for the fluctuations in gas pressure are still relatively little studied, but some of them can be considered quite established. The gas pressure in the chamber can primarily fluctuate due to disturbances in the gas-air path of the engine. Fluctuations in gas pressure can sometimes be caused by fluctuations in the pressure of the fuel supplied to the combustion chamber.

A study of the pressure in the combustion chambers, carried out using the readings of special instruments recorded by an oscilloscope, showed the presence of very noticeable pressure fluctuations with frequencies from 20 Hz to 250 Hz, with an amplitude of up to 15% of the average pressure in the chamber. In some cases, the frequency of pressure fluctuations reached 60,000 Hz with amplitudes up to 70% of the average pressure in the chamber. Usually, one of the observed oscillation frequencies of air or gas pressure resonates with the natural oscillations of the chamber parts.

3. Measurement results Determination of eigen frequencies of the shells of the combustion chambers of GTE

Investigation of the vibration modes of cylindrical and conical shells as applied to the combustion chambers of a GTE allowed [6] to obtain formulas for determining the frequencies of natural vibrations and to verify the obtained formulas experimentally. A simplified model of the annular combustion chamber of the AL-31ST engine was used as the object of modeling (Fig. 2).

The following data was taken as an input:

- temperature 873 K;
- operating pressure 416 kPa;
- frequency range from 0 Hz up to 10,000 Hz.

Figure 2. Simplified combustion chamber model

Figure 3. Forms of axisymmetric vibrations of a cylindrical shell

Theoretical and experimental studies have shown that the shell can be considered as freely supported, since the pinching effect due to the small thickness of the material extends over a short length. Circular frequencies $f$ of axisymmetric natural vibrations of a cylindrical shell (Fig. 3), freely supported at the edges, are determined by the following formulas:
– for the first mode of vibration:

\[ f_1^2 = \frac{B}{mR^2} \left[ 1 + k \left( \frac{\pi R}{l} \right)^4 \right], \quad (1) \]

– for the second mode of vibration:

\[ f_2^2 = \frac{B}{mR^2} \left[ 1 + 16k \left( \frac{\pi R}{l} \right)^4 \right], \quad (2) \]

where

\[ B = \frac{E\delta}{1-\mu^2} \] – quantity conventionally called tensile stiffness of the shell;

\[ E \] – elastic modulus of material;

\[ \delta \] – shell thickness;

\[ \mu \] – Poisson’s ratio;

\[ m \] – mass per unit area in kg;

\[ l \] – shell length.

For thin and long shells (small values \( k \) and small ratios \( R/l \)) frequencies \( p_1 \) and \( p_2 \) differ little from each other. For thick and short shells, the frequencies differ significantly. The calculated eigen frequency of natural vibrations of the combustion chamber of the AL-31ST engine is \( f_1=f_2=41 \) Hz.

The chain of the path of passage of the gas-air mixture through a set of chambers, each of which is a resonant cavity with a high quality factor and a narrow bandwidth of the frequency response, of the order of a few Hz, represents a potential threat of surge when the oscillations of gases coincide with the natural resonance frequency of the chamber, increasing the amplitude of acoustic vibrations in time.

To detect pre-surge phenomena, the approach of gas vibration frequencies to the natural resonance frequency of the chamber, it is possible to control the temperature with a high-speed differential meter and a high-speed flow meter [7] inside the chambers, as well as using an ADcmXL1021-1 vibration sensor mounted on the outer shell of the engine.

The developed sensor combines a high-precision MEMS accelerometer and the signal processing capability of intelligent sensor (Fig. 4). Signal processing includes high speed data sampling (220 ksamples / s), 4096 bit data memory, filtering, window smoothing, fast Fourier transform, configurable spectral or temporal statistics alarms, and error flags.

![Vibration sensor](image)

**Figure 4. Vibration sensor**

4. **Conclusion**

A differential system for measuring the temperature of gas turbine engines, which has a speed of three orders of magnitude higher than thermocouples, will allow the creation of an automatic control system of a GTE for automatic take-off and landing, save fuel and increase the resource.

A new approach to identifying the causes of surge phenomena will create an automatic control system to prevent it.

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