CORRECTING FREQUENCY CHARACTERISTICS OF PRESSURE PULSATIONS PROBES (REVIEW)

Asgat Gimadiev, Nikolas Bystrov, Dmitry Stadnik, Alexander Igolkin

Samara National Research University, Institute of Engine and Power Plant Engineering, Samara, Russian Federation, email: sdm-63@bk.ru

Marat Gimadiev

The Gimalai Ltd, Zavodskoe shosse, Samara, Russian Federation, email: gimalai@gimalai.com

Unsteady pressures are considered as one of the main parameters in the final design of gas turbine engines and also in other power plants. In this scientific paper special focus lies in the accuracy of the unsteady pressure measurements. The gas flow with high temperature and the restrictions on the sensor mounting place dimensions often do not allow the sensor to be mounted directly at the pressure measuring point. Therefore, it is necessary to connect the sensor to the process using a pressure transmission line. It's a well known fact that the resonance frequencies occur's in the pressure transmission line systems, and it leads to an additional dynamic error into unsteady pressure measurement. To correct the unsteady pressure during experiments, in-line compensation elements in the pressure transmission line system are used. Devices consisting of a dynamic pressure sensor, a pressure transmission line, and a correcting element in the technical literature have been introduced and its called as called the pressure pulsation probe. Considering the importance of the constant growth of the modern engine thrust and, correspondingly, the working process temperature increase, the authors are interested to carry out an overview analysis of effectiveness of the correcting elements based on available patents, articles and monographs. This paper deals with acoustic correcting elements with distributed and lumped parameters, their advantages and disadvantages are explained, and also presented the methods for calculating the frequency characteristics of probes and their application in the processing of experimental data. The analysis is carried out without considering the error of the pressure pulsation sensor itself. The article will be of interest to developers of pressure pulsation probes used in the extreme conditions of their operation, engineers and technicians for GTE testing and improving.
Keywords: pressure pulsations, measurement, probe, correction of characteristics.

1. Introduction

When developing and operating a gas turbine engine and rocket engines, it is important to have reliable information about the dynamic processes that arise in them. One of the main parameters that carry information about the working processes in engines is pressure, which accounts for 25 ... 30% of measured parameters. The unsteady pressure in the air intake of the gas turbine engine can cause a drop in the gas-dynamic stability of the compressor, it causes vibrations in the combustion chamber and lead to intense vibrations of the engine components [1-8]. To obtain reliable data on the pulsating state of engine assemblies, it is necessary to see that the dynamic error in measuring the pressure pulsations does not exceed 5...10 % in the frequency range 5 ... 5000 Hz. There are a number of suppliers of high-temperature unsteady pressure sensors, but often the temperature of the gas in the control objects exceeds the permissible values for the sensors, and their sensitivity is insufficient to detect weak pressure pulsations sometimes in the gas turbine. Therefore, an acoustic probe consisting of an unsteady pressure transmission line from the process to the pressure sensor and acoustic correction element (CE) is used, which eliminates the occurrence of resonance oscillations and, thereby, reduces the additional dynamic error of the probe. In connection with the improvement of engines, taking pressure pulsations into the count, the necessity of the probe application has increased in recent years [4]. Till date, patents on probes have been published [7-24], a number of theoretical and experimental studies of dynamic processes in them have been carried out, their designs have been developed [27-63], but there is no peer review of their effectiveness and recommendations for the CE use. The paper analyzes the efficiency of acoustic CE with distributed and concentrated parameters, a review of the work in which the methodology and algorithm for calculating the frequency characteristics of the probe are described, taking into account the non-stationary friction in the pressure transmission line, the change in area and temperature along its length, the volume of the pressure sensor chamber, the mean pressure in the monitoring object, circuits and CE parameters.

2. Acoustic probe without correcting element

The first probes used in the machinery without correcting elements (Fig. 1) [9, 27]. Such kind of probe in general, is the irregularity of amplitude-frequency characteristic (AFC), leading to significant additional dynamic error in the measurement of the unsteady pressure, depending upon the frequency of the pressure pulsation ω , the diameter and length of the pressure transmission line, the viscosity of the fluid, the volume of the chamber on the surface of the transducer.

In general, the frequency response of the probe is determined by equation $W(\omega) = p_2/p_1$, where $p_1 = B_1 e^{j\varphi_1}$, $p_2 = B_2 e^{j\varphi_2}$ are the complex amplitude of the pressure oscillation, respectively, at the inlet of the pressure transmission line and the transducer; B_1, φ_1; B_2, φ_2 - respectively the amplitude and the initial phase of the pressure fluctuations at the inlet of the pressure transmission line and the transducer; $j = \sqrt{-1}$.

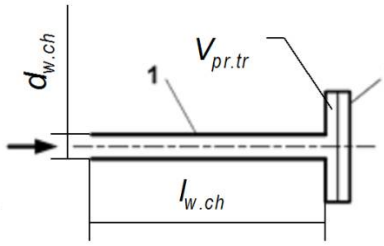


Fig. 1. Schematic diagram of the acoustic probe without the correct element: 1 – pressure transmission line; 2 – dynamic pressure transducer.

AFC of the probe is determined by dependence $M(\omega) = \lfloor p_2/p_1 \rfloor = B_2/B_1$, and phase-frequency characteristic (PFC) by the equation $\beta(\omega) = argW(\omega) = \varphi_2 - \varphi_1$. The geometrical parameters of the pressure transmission line and the highest frequency of the measured pressure fluctuations ω_{max} with an acceptable dynamic error of the probe Δ_{ad} determined from the condition $|1 - M(\omega)|_{\omega \in [0, \omega_{max}]} 100\ \% \leq \Delta_{ad}$. The method of calculation of the probe without the CE is given in [3].

3. Probes with correcting elements in the form of a long line

A long pressure transmission line with a diameter equal to the diameter of the waveguide as a probe correcting element have been applied a long time [1,5,13,15,46]. For example, the known design of the probe with termination load in the form of a long pipeline (about 24 m long) (Fig. 4), to ensure the uniformity of AFC in the frequency range (0...10) kHz with an error of less than 5 dB [1]. In the study of pressure fluctuations at the inlet of the compressor and in the exhaust of the gas turbine engine was used in the probe of matching line length reaches to 91 m. In [54,55,57] the results of analytical and experimental research on frequency response characteristics of the 4 mm diameter probe with different lengths from 700 mm up to 2 m at normal and increased up to 100 °C environment temperature are presented. The static pressure in the experiments was changed from 0.14 MPa to 2.64 MPa. Line length of 30 m and 60 m were used. Analytical calculations of AFC in the framework of the developed mathematical model has received experimental confirmation.

In a probe for measuring unsteady pressure in the combustion chamber of the stationary GTE a long pipeline of 40 m laid in the form of a compact coil and is connected to the output of the waveguide [21,55] (Fig. 2). To remove hot gas from the pressure transmission line, the air supply is arranged with lower temperature and greater relative pressure to the exit of a long line. The gas temperature at the location of the pressure sensor does not exceed 200 °C. Similar to the design of the probe [25], shown in Fig. 3, provided an additional adjustable volume chamber connected to the pressure transmission line for fine tuning of the AFC in a narrow range of frequencies.

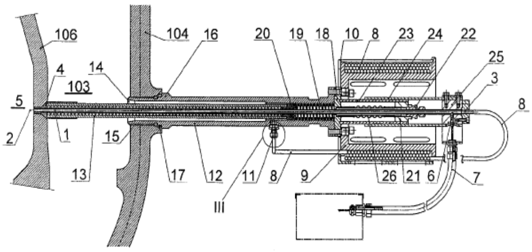


Fig. 2. A device for unsteady pressure measurement

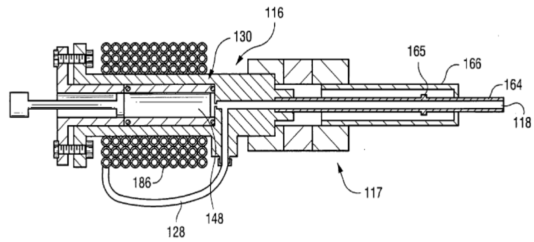


Fig. 3. Turbine pressure fluctuations control probe

The authors [22], used a long line for correcting the frequency response characteristics of the short (50 mm) waveguide with the hot gas removed in the process zone as in [25]. To reduce the length of the correcting lines in a number of works, it is proposed to put the damping insert inside it [13,15], for example, made of a porous material MR [13]. To ensure the required accuracy of the probe in a given frequency range the length of the matching pressure transmission line with a porous correcting element needs 3..5 times to be greater than the length of the waveguide [5]. In [3,5] proposed a scheme of the probe with the correcting element in the form of a bundle of capillary channels, the total input acoustic impedance of which is equal to the characteristic impedance of the waveguide.

4. Pressure probes with acoustic RC - filters

As discussed above the correcting elements in the form of long lines, providing the necessary alignment of the AFC, have a significant drawback – large size and weight. This drawback does not have the AR with correcting elements the in the form of acoustic low-frequency RC-filter. The input impedance of this filter is selected to be equal the characteristic impedance of the waveguide in the desired frequency range of the specified parameters of the working environment. An example of implementation of the probe with such RC filter is the aerometric receiver for the gas stream unsteady pressure measurement in the [10-12].

The drawback of the correcting element schemes is the dependence of the RC-filters characteristics upon the static pressure. In some cases, the design of the probe is simplified if the acoustic RC-filter is connected in series between the waveguide and pressure transducer [14,39]. However, the use of a sequentially located RC-filter does not ensure the uniformity of the probe AFC in the frequency range lying above the first resonance frequency of the undamped waveguide. Such a solution is used in the construction of probes. It should be noted the efficiency of the acoustic RC-filter in the AP, containing differential pressure sensor [44].

5. Pressure probes with correcting throttling elements

Given the significant weight and sizes of long pressure transmission lines as a probe correcting element, the authors propose a correction scheme based on the use of concentrated throttling elements with linear acoustic characteristics [3,5]. In Fig. 4 shown the diagrams of the probes with the correcting elements in the form of throttling elements synthesized under the assumption of no losses along the length of the waveguide and zero volume of the chamber at the pressure sensor surface from the conditions: $M(\omega) = 1_{\omega\in[0,\infty]}$ and $\beta(\omega) = -\omega \cdot l_{w.ch}/a$. Depending on the schema of the probe the throttling correcting elements take the values of acoustic impedance, a multiple of the wave resistance of the waveguide $Z_{w.ch} = \rho \cdot a/A_{w.ch}$. Such chokes are concentrated elements made of the porous MR material [51].

The above AR schemes based on the use of lumped chokes and surge chambers have the advantage - small size and weight. However, their AFC is sensitive to the mean pressure as the resistance of the throttling correcting elements depends on the density of the media. As it depends on pressure, the probe with porous chokes can be used for the pressure fluctuations measurement in objects operating at steady state. In [22,23,61,63] proposed a probe with an automatically tunable acoustic impedance of the choke at the mean pressure.

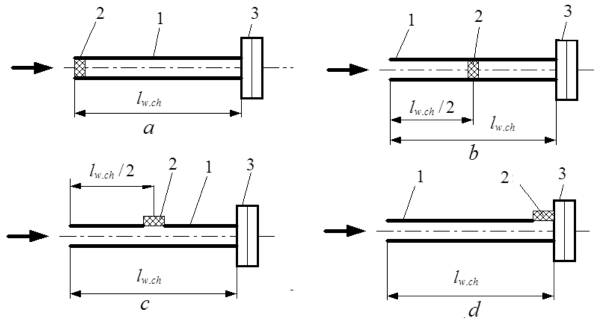
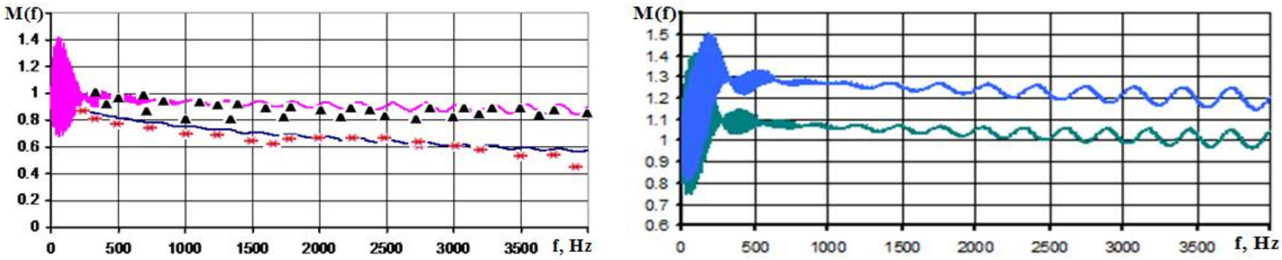


Fig. 4. Schematic diagrams of unsteady pressure acoustic probes with throttling correcting elements: 1 - waveguide; 2 - choke with an active resistance equal to $Z_{thr.el} = Z_{w.ch}$ - scheme a; $Z_{thr.el} = 2Z_{w.ch}$ - scheme b; $Z_{thr.el} = Z_{w.ch}/2$ - scheme c; $Z_{thr.el} = Z_{w.ch}$ - scheme d; 3 – pressure sensor

6. The programs for designing the acoustic probes and digital filtering their frequency response characteristics

In [50,58] proposed impedance method for the calculation of the pressure probes frequency response characteristics and the authors developed the algorithm and it's program implementation. The program for the AR calculation are considered: sensor type (pressure or differential pressure); the type of waveguide (uniform, non-uniform in temperature along it's length, non-uniform in cross sectional area, non-uniform both in temperature and cross sectional area); the presence of correcting elements (with or without it); the scheme of the probe AFC correction (long pressure transmission line, bundle of capillary channels, with a porous vibrations absorber, with lumped chokes). The computer program RUDIP is written in C++ and can calculate the AFC and APF, the module and the argument of the acoustic input conductivity of the pressure probe; draw graphs of characteristics; store data in the form of graphs and tables; input and edit of the pressure probe parameters. The program calculation results of the pressure probe with long pressure transmission line are confirmed by experimental data from [56] (Fig. 5).



a b

Fig. 5. AFC of the pressure probe with a long pressure transmission line: the 4 mm diameter 0.7 m length waveguide with the volume of the chamber at the surface of the pressure transducer sensor 20 mm^3, the long line diameter 4 mm, length 30 m at temperature 300 K and the mean pressure 0.14 MPa (—— theory; * - experiment), 2.64 MPa (—— - theory; ▲ - experiment) (a); when the inlet temperature probe 1000 K (—— - theory) and 500 K (—— - theory) exponentially falling to 300 K along the length of the waveguide at an mean pressure of 2.64 MPa (b).

Residual dynamic error of a pressure probe due to inconsistencies of the correcting element to the waveguide, is proposed to compensate for the digital correction using the authors' program is based on the calculated or experimentally obtained data on the stand of its AFC. The description of this program and the results are verified carefully and presented in paper [52].

Conclusions

Analysis of the means for correcting the frequency response characteristics of the acoustic pressure probes allowed us to draw the following conclusions:

- in general, the dynamic error of the pressure probe or its amplitude-frequency characteristic depends on the parameters of the monitoring object at its input (mean pressure and its fluctuations pattern, gas temperature), on the diameter, length and non-uniformity of the pressure transmission line, the volume of the chamber at the surface of the pressure transducer and its sensitive element compliance, the degree of consistency of the parameters of the correcting element with the waveguide;
- long "endless" pressure transmission line, In spite of its weight and size, is one of the effective elements of the pressure probes, the length of which, depending on the mean pressure can reach 20-50 m, and the higher the pressure, the longer the line must be;
- when using the long pressure transmission line the dynamic error still occurs at low frequencies due to quarter-wave resonance of the longest line with the waveguide, and the resonance of the waveguide chamber at the surface of the pressure transducer, depending on the diameter and length of the waveguide, the length of the correcting element and mean pressure;
- with a small change in mean pressure in the test object, it is appropriate to apply the small correcting chokes with linear active resistance, a multiple of the characteristic impedance of the waveguide probe. This requirement is almost satisfied the chokes made of porous MR material;
- when the mean pressure in the test object changes in a wide range, the pressure probe with the RC-filter correcting choke, the impedance of which is automatically rebuilt by the mean pressure used
- the developed algorithm and computer program for calculating the pressure probes frequency response characteristics, allowing to choose the parameters of the acoustic model of correcting elements that provide unsteady pressure measurement in the maximum possible for the selected scheme frequency range, to investigate the influence of non-uniformity of the temperature and the cross section area of the waveguide to the measurement dynamic error;
- as a result of calculations, it is established that the temperature non-uniformity of the waveguide elevates the frequency response of the pressure probe to the extent of ¼ from the relationship of the temperature at the inlet of the probe and a pressure transducer;
- proposed digital correction of GTE pressure fluctuation spectra measured during the test, according to the calculated or experimentally defined on the stand of frequency response characteristics of the pressure probe as close to operating conditions.

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