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On the Development of a Compact Acoustic Probe for Pressure Oscillation Measurements in Gas Turbine Engine

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Abstract

In experimental fine-tuning of aircraft and ground-based gas turbine engines the gas-air line pressure oscillations is a highly informative parameter. Because of high temperatures and vibration levels the pressure sensors do not meet tolerances and thus they are connected to the measuring point by supply channels forming an acoustic probe. The resonant pressure oscillation amplification in the probe, reducing the accuracy of the measurement, occurs if no correction elements are used. Applicable correction elements in the form of long lines are of limited use due to their large size. The authors suggest corrective compact devices capable of measuring the acoustic pressure oscillations by the probe in a wide range of medium pressure. The corrective devices are implemented as a set of capillary channels and a porous MR throttle made of 0.09 mm diameter wire spiral by mold compression regulated by the average acoustic pressure. The technique of selecting parameters and design of the corrective devices are presented herein.

Keywords: gas turbine engine, pressure oscillations, acoustic probe, waveguide channel, dynamic error, correction element, adjustable RC-filter, frequency response, stand, experiment, analysis

1. Introduction

Pressure oscillations in gas-air line of gas turbine engine are initiated by stall performance of the compressor, vibratory combustion in combustion chamber and vortex paths behind bluff shaped engine elements. Pressure oscillations considerably affect gas dynamic stability of the compressor. Therefore, precise measurement of pressure oscillations is very important in experimental development of gas turbine engine. Numerous publications by Russian and foreign authors attest to the above mentioned fact, e.g. [1-8]. To provide high-accuracy measurements of pressure oscillations the theoretical researches and engineering designs of probes for pressure oscillation

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measurement have been carried out, the quick-changing pressure sensors cannot be connected directly to the measuring point. To suppress resonance oscillations in supply waveguide channels correction elements [9-11] have been used. The most effective way to suppress resonance oscillations in probe supply channels is so called “long line” [12-14].

The authors have already developed the probe for higher medium pressure and temperature conditions in flow duct of gas turbine engine, with 40 m waveguide channel of 6 mm diameter [15]. Due to the acoustic probe's large size and heavy weight it is often impossible to place the probe in the test stand area. In this respect development of compact and at the same time high-accuracy acoustic probe to be used in development testing of gas turbine engine is of particular significance.

2. Correction element as a set of capillary channels

The sizes of corrective or tuning device in the form of a long line can be reduced by increase of energy consumption of transferred pressure oscillations. For this purpose it is suggested to use a set of capillary channels with total cross-section area equal to waveguide cross-section area.

The authors have developed a design procedure in the form of group of capillary channels and corresponding program component allowing to design amplitude frequency response (FRES) of supply pipeline channels with the group of capillary channels in the form of a tuning device. [16].

![Diagram of pneumatic probe with capillary correction element](image)

Fig. 1. Diagram of pneumatic probe with capillary correction element:
TOB – test object; WAH — supply channel; SN – pressure oscillation sensor; CAP – set of capillary channels.

In order to generate algorithm for selection of device optimal parameters with corrective element capillary the analysis of its influence on FRES measuring loop was implemented.

Suppose total capillary cross-section area equals to supply channel cross-section area or $n_{cap} = \frac{d^2}{d_{cap}^2}$. Analysis of FRES loop shows that the bigger the quantity and length of capillaries the smoother the pressure oscillation transmission. However, if the increase of capillary channel length is more than a specified rate, the effect of capillary length on FRES smoothness weakens.

3. Correction element as an adjustable RC-filter

The research work [15] shows that for acoustic probes a small-size RC-filter can be used as an alternative to corrective element (CE) in the form of long line. As for the CE weight it can be reduced considerably in comparison with the long line weight providing light alloys are used.

Design made according to RUDIP* program [16] shows that optimal alignment is achieved when CE impedance equals to wave impedance of supply waveguide channel at enough expansion chamber capacity.

*RUDIP - program complex allowing to design amplitude frequency response (FRES) various types of acoustic probes.
As far as the wave impedance of supply channel changes linearly with the change of absolute pressure of gas medium it is advisable to apply an adjustable throttle in the present CE design. The principle of throttle length adjustment depending on the change of medium pressure is realized in this design. It has been proposed to use throttles made of MR material consisting of 3-element MR package (Fig. 2) for adjustable impedance.

![Fig. 2. Acoustic probe with corrective RC-filter construction scheme: 1 – tube for connection to a turbine combustion chamber; 2 – the sensor of the pressure pulsations PCB M102A07; 3 – fitting; 4 – ferrule; 5 – welded case; 6 – tube; 7 – slide; 8 – MR throttle; 9 – plug; 10 — bellows adapter; 11 – coil spring; 12 – bellows; 13 – locking stop; 14 – bellows cover; 15 – adjustment screw.](image)

The throttles are fixed at the end of perforated tube 6 in such a way that the perforation is covered lengthwise by the slide 7 driven by bellows 12. The bellows is loaded by internal pressure in RC-filter expansion chamber on the one hand and by spring force 11 and atmospheric pressure on the other hand. Balance of above mentioned forces ensures required bellows deformation and, consequently, desired length of oscillation throttling through MR-throttles.

4. Design of correction element

For an adjustable throttle of RC-filter made of MR material the impedance is proportional to restrictive length. Hence follows the equation:

$$\frac{\Delta l_{\text{init}}}{\Delta l_{\text{init}} + \Delta L} = \frac{p_{\text{min}}}{p_{\text{max}}}$$

(1)

From the equation (1) we can find out:

$$\Delta l_{\text{init}} = \frac{r \cdot \Delta L}{1 - r}$$

(2)

where $r = \frac{p_{\text{min}}}{p_{\text{max}}}$; - bellows operational stroke; - initial gas restrictive length in the throttle at initial operational pressure of acoustic probe; $p_{\text{min}}$ – minimum gas pressure (start of work); $p_{\text{max}}$ – maximum pressure for the probe to work in design conditions.

Apparently the total throttle length will be equal to

$$l_{\text{thr}} = \Delta l_{\text{init}} + \Delta L$$

(3)

Resistance of cylinder MR throttle is defined by the expression [17]:

$$R_{\text{thr}} = k_1 \frac{(1 - F_{\text{por}})^2}{F_{\text{por}}^3} \cdot l_{\text{thr}} \cdot \mu \cdot \frac{l_{\text{thr}} \cdot \mu}{d_{\text{wire}} \cdot S_{\text{thr}}}$$

(4)
where \( k_1 = 75 \) — MR material structure coefficient; \( F_{\text{por}} \) — MR throttle porosity; \( \mu \) — gas dynamic viscosity; \( d_{\text{wire}} \) — diameter of wire stock for MR throttle; \( S_{\text{thr}} \) — cross-section area of cylinder throttle.

At the same time the resistance of supply waveguide is defined by the following expression [8]:

\[
Z_{\text{wav}} = \frac{p}{R_g \cdot T \cdot S_{\text{wah}}}, \tag{5}
\]

where \( Z_{\text{wav}} \) - wave impedance of cylinder tubing (supply channel); \( p \) — process absolute pressure; \( R_g \) - gas constant; \( T \) – absolute temperature; \( S_{\text{wah}} \) - cross-section area of tubing.

If we equate \( R_{\text{thr}} \) to \( Z_{\text{thr}} \) at process pressure corresponding to maximum designed value, then, taking into account the dependence (3), we can define the complex \( K(F_{\text{por}}) = (1 - F_{\text{por}})^2 / F_{\text{por}}^3 \) providing \( S_{\text{thr}} = S_{\text{wah}} \)

\[
K(F_{\text{por}}) = \frac{(p_{\text{max}} - p_{\text{min}}) \cdot a \cdot d_{\text{wire}}^2}{k_1 \cdot R_g \cdot T \cdot \mu \cdot \Delta L}, \tag{6}
\]

In case the RC-filter operates only due to the bellows flexibility. Maximum force developed by bellows at operating stroke = 10 mm, is equal to 165 N. From here we evaluate the excessive gas pressure \( (p_{\text{max}})_{\text{exc}} = N_{\text{bell}} / A_{\text{bell}} \), where \( N_{\text{bell}} \) - the spring force; \( A_{\text{bell}} \) - effective area of bellows. For the bellows presented herein \( A_{\text{bell}} = 2.34 \text{ cm}^2 \). From here we evaluate \( (p_{\text{max}})_{\text{exc}} = 0.7 \text{ MPa} \).

Taking into account atmospheric pressure we evaluate maximum absolute pressure \( p_{\text{max}} = 0.8 \text{ MPa} \).

Let's evaluate MR throttle characteristics for RC-filter. We take:

\[
p_{\text{max}} = 0.8 \text{ MPa}; \quad p_{\text{min}} = 0.1 \text{ MPa}; \quad a = 341 \text{ m/s}; \quad d_{\text{wire}} = 0.09 \text{ mm}. \]

From ratio (7) it follows: \( K(F_{\text{por}}) = 1.63 \). Under known value \( K(F_{\text{por}}) \) according to the curves in Fig. 3 we evaluate \( F_{\text{por}} = 0.52 \).

The bellows characteristics should comply with the following requirements:
- to have a linear characteristic of “compressive force - deformation”;
- to have the operating stroke not less than 10 mm;
- to be designed for external loading mode;
- to have maximum process pressure corresponding to the maximum process pressure of acoustic probe;
- to have linear characteristic;
- not to have hysteresis;
- to work at temperature up to 100 °C;
to stand 10000 complete operating strokes.

As a result of analysis of available bellows we selected the “Single-layer bellows” with internal bore diameter of the rib 16 mm.

The important characteristic of the bellows is its stiffness. Fig. 4 shows the characteristic which was evaluated experimentally.

![Fig. 4. Characteristic of bellows strength load.](image)

5. Experiments

Fig. 2 shows construction diagram of experimental sample of the probe with RC-filter and pressure sensor PCB M102A07. Frequency tests of experimental probe were carried out at the SSAU frequency stand (Fig. 5) with medium pressure from 0.2 to 0.8 MPa and pressure oscillation amplitude up to 10 kPa in the frequency range: 5…800 Hz.

![Fig. 5. General layout of the unit for experiments on acoustic probe frequency response data: 1 — pressure gauge (2.5 MPa); 2 — pressure oscillation monitor sensor; 3 — pulsator chamber; 4 — pulsator; 5 — pulsator electric drive; 6 — mounting plate; 7 — buffer tank; 8 — valve; 9 — acoustic probe supply pipe.](image)

The technique for processing experimental data obtained from the experimental sample of acoustic probe and the monitoring pressure oscillation sensor located in dynamic chamber of the pulsator, is based on the comparison of registered pressure oscillation amplitudes.
Signals from the probe pressure oscillation sensor and monitoring sensor came to the panel input MIC-201 of the measuring and computing complex MIC-026 and with the help of the program Recorder were recorded to the hard disc.

6. Analysis of acoustic probe experimental frequency response

Fig. 6 shows FRES of designed experimental probe with medium pressure 0.5 MPa. Analysis of obtained experimental FRES shows that acoustic RC-filter performs its functions on creating conditions of non-reflecting load and providing smooth transmission of pressure oscillations through the waveguide channel of the probe.

![Fig. 6. Amplitude-frequency response of the probe with supply waveguide: length = 910 mm, internal diameter = 6 mm, medium pressure 0.5 MPa (1 – without RC-filter; 2 – with adjustable RC-filter).](image)

Frequency tests of experimental probe were carried out at the SSAU frequency stand (Fig. 6) with medium pressure from 0.2 to 0.8 MPa and pressure oscillation amplitude up to 10 kPa in the frequency range: 5…800 Hz.

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Signals from the probe pressure oscillation sensor and monitoring sensor came to the panel input MIC-201 of the measuring and computing complex MIC-026 and with the help of the program Recorder were recorded to the hard disc.

7. Conclusion

Theoretically substantiated and developed design of experimental probe for measuring pressure oscillations in combustion chamber of gas turbine drive with automatic adjustable acoustic RC-filter enabling to fulfill measurements in a wide range of medium pressure is presented herein.

Later on it is assumed to improve the design of RC-filter for more accurate adjustment of its characteristics to the parameters of waveguide channel under change of medium pressure in the monitor object. Besides, it is planned to reduce its weight.

References

[1] Dowling, A. P., Morgans, A. S. Feedback control of combustion oscillations. Annual Review of Fluid Mechanics, № 37, 2005.- P.151-182.
[2] Canbazoglu, S., Yakut, K. Reduction of peak amplitudes of pressure fluctuations in turbulent pipe flow using vortex generators and compliant boundaries. HVAC and Research, № 11(3), 2005.- P. 487-498
[3] Combustion Instabilities in Gas Turbine Engines: Operational Experience, Fundamental Mechanisms, and Modeling. Yang, Vigor Lieuw en, Tim. American Institute of Aeronautics and Astronautics Location. 2006.- 672 p.

[4] Shoutapalli, I., Krothapalli, A., Arakeri, J.H. An experimental study of an axisymmetric turbulent pulsed air jet. Journal of Fluid Mechanics, № 631, 2009. - P. 23-63.

[5] Instantaneous pressure measurement in pulsating high temperature internal flow in ducts Benajes, Jesus; Bermudez, Vicente; Climent, Hector; Rivas-Perea, Manuel. Applied Thermal Engineering 61.2 (Nov 1, 2013). - P. 48-54.

[6] Shorin, V.P., Gimadiev, A.G., Bystrov, N.D. Data transfer hydraulic and gas circuits [Text] // M.: Mashinostroenie, 2000. - 328 p. (in Russian)

[7] Shorin, V.P., Shahmatov, E.V., Gimadiev, A.G., Bystrov, N.D. Acoustic methods and measurement instruments for pressure oscillations // Samara: SSAU, 2007. – 132 p. (in Russian)

[8] Furletov, V.I. Thermoacoustic stabilization in low emission combustion chambers. / Furletov, V.I., Vedeshkin, G.K. // Environmental problems of aviation. Part 3. Emission of harmful substances of gas turbine units. / Under the editorship of Yu.D. Haleckiy, -M.: TORUS-PRESS, 2010.-p.433-450.

[9] Petunin, A.N. Methods and measuring instruments for gas flow parameters. – M.: Mashinostroenie, 1972.- 332 p. (in Russian)

[10] Gimadiev, A., Bystrov, N. (1981) Dampfung und Korrektur der dynamischen charakteristika von runchden Flussigkeitskanalen von Regel- und Kontrollsystemen.- H. Fachtagung, Hydraulik und Pneumatik, Vortrage teill 4. Fachtag und Hydraulik und Pneumatik, Vortrageteils, DDR, Magdeburg. - S. 604-609.

[11] Gimadiev, A., Bystrov, N. (1983) Korrekturr der Frequeuz gauge der Hydraulik –und Grasinformations-Ketten 5.Fachtagund Hydraulik und Pneumatic, Vortrageteils, DDR, Drezden. - S. 347-359.

[12] Furletov, V.I., Dubovitsky, A.N., and Khanyan, G.S. Determination of frequency characteristics for "transducer waveguide" system under high gas parameters // IGTC 2007 Tokyo TS-160. Proceedings of the In-ternational Gas Turbine Congress 2007 Tokyo, December 3-7, 2007.

[13] Furletov, V.I. Determination of frequency response of the measurement system "pressure oscillation sensor-waveguide" under high gas conditions./ Furletov, V.I., Dubovitsky, A.N., Khanyan, G.S. // Development of test instruments and methods for aero engines (Collection of articles). Group of authors – M.: CIAM, 2010.-252 p. (in Russian)

[14] Shorin, V.P. Development and experimental study of frequency response of acoustic probes for pressure oscillation measurement in gas generators. /Shorin, V.P., Gimadiev, A.G., Bystrov, N.D., Il’inskiy, S.A., Aleksandrova, T.G. // SSAU Bulletin (National Research University), 2012. – №3(34)-2.- p. 269-274 (in Russian).

[15] Gimadiev, A.G. Development of a small-size acoustic probe for pressure oscillation measurement in gas dynamic duct of GTD / Gimadiev, A.G., Bystrov, N.D., Il’inskiy, S.A. // SSAU Bulletin (National Research University), 2014. – № 1 - p. 98-106 (in Russian).

[16] Gimadiev, A.G. Development of technique and computer program for nonhomogeneous gas measuring chains / Gimadiev, A.G., Bystrov, N.D., Ustinov, A.V. // SSAU Bulletin (National Research University), 2012. – №3(34)-2. – p. 263-268 (in Russian).

[17] Izzheurov, E.A. Study of hydrodynamic and filtering characteristics of elastoporous MR material for aero engine systems [Text]: Cand.Sc.thesis in Eng./ Izzheurov, E.A. – Kuibyshev: KuAI, 1975. -137 p. (in Russian)