HEATPROOF MICROWAVE SENSORS. FLAME PARAMETERS DIAGNOSTICS IN COMBUSTION CHAMBERS OF THE DIFFERENT ENGINE TYPES.

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Abstract

Combustion processes study by using microwaves probing of the flame has been applied already for some years [1, 2]. Compact microwave sensors with frequency exit and small-sized flush-mounted antennas [3] enable to use this approach for in-process measurement of the propulsion thermal power engines (TPE) in operating conditions and in real time. Sensors advantages: nonperturbative control (including small engineering changes in combustion chamber), sufficiently powerful and noise-immune measuring signal and quick-action, that is inherent for radiolocators, which enables, specifically, to detect pre-emergency situation on a very early stage.
Complex of the noises with different nature and correspondingly with different mechanism of responses forming leads to the frequency modulation of monitoring signal. This situation causes significant mistakes in the process of diagnostics systems engineering [2], including multichannel systems, and decreases control effectiveness.
Purpose of the work: estimation of the frequency band of responses on the flame parameters for two types of active oscillating sensors: electron density, self radiation, fluctuation heating of antenna and resonator as well as consideration of anisochronism and vibration actions.
Checking information of the sensor's signal consists in frequency measurement and spectral density of its fluctuations. This is why measurement process finishes by frequency detection with estimation of the spectrum of received signal.
Theoretical estimations of the spectral density were obtained by solution of differential equations for two types of the sensors- active oscillating sensor and autodyne sensor. Amplitude-frequency characteristics were determined.
Has been shown, that for the active oscillating sensor of the range of 2...4GHz, bandwidths of responses are from unites to tens of MHz for electron density, units of KHz for vibrations and tens of Hz for the temperature. For the autodyne sensor the first index is appreciably smaller.
Microwave sensors of the flame dielectric permittivity are mounted on combustion chamber wall and subjected to several hundred degrees heating by [4]. Oscillating diode temperature was determined on the basis of the heat transmission processes analysis; temperature errors- static, fluctuation and dynamic, caused by heating, were found. Circuit and constructional measures of thermal protection including error decrease were discussed.

Introduction

It is considered, that methods and equipment of the microwave diagnostics, including combustion modes in thermal power engines (TPE), have been adopted from plasma diagnostics. But during creation, testing, experiments and practical application of these methods and equipment lots of distinctions were found.
For the microwave diagnostics of combustion processes following features are typical:

- Limitation of the well known methods of plasma diagnostics, especially refraction and cutoff methods.
- Creation of the specific manner of microwave diagnostics.
- Differentiation of the manners, which are suitable for scientific (test bed) experiments, and manners, which are oriented on the in-process measurement in actual operating conditions of TPE.
- Deficiency of alternative microwave or other methods, which are able to estimate accuracy of control and testing apparatus.
- An accent on the circuit and constructive development of the sensors or generator of the probe oscillation with antenna; rigid connection of devices construction (especially sensors) with combustion chamber construction.
- Attention to the electrotechnical materials features such as erosion resistance, heat and temperature conductivity, heat expansion, immunity to combustion products deposition.
- Development of the methods of initial measuring signal processing in a pace of the real technological process, including data capture about all the noise types.

Two microwave sensors of the pointed class found their application. In both of them sensing element is a flush-mounted slit antenna, its aperture turned into combustion chamber. In the first type sensor [3] antenna has been constructively combined with resonator. It excites by the loop current and its impedance directly turns into informative parameter of the monitoring signal – into the probing frequency. In the second type sensor [6] antenna is remote and unmatched, its influence at the frequency is determined by reflection. Principle of the monitoring signal (MS) forming is autodyne.

The main advantage of these sensors is their capability of monitoring of the spectrum fluctuations shape of the most dynamic plasma parameters- electron density N_e and temperature T. From the thermodynamics position [7] spectrum is more informative than usual averaged values.

Monitoring signal spectrum is contaminated by interferences. This caused not only by multifactorial flame action (heating, erosion, vibrations, self-radiation of the plasma), but also by features of active oscillators dynamics (anisochronism, incidental amplitude modulation), as well as features of sensor's constructions (materials, elements configuration).

Purpose of the work

Taking into consideration all pointed above, monitoring signal reprocessing is very important. Its efficiency grows under multichannel monitoring [2] and requests the knowledge of sensor's sensitivity in relation to monitoring and interference influences as well as familiarity with frequency bands of corresponding responses. This work is dedicated to reveal and comparison of indicated features of two sensors, mentioned above.

Analysis of an active oscillating sensor's dynamics

Antenna's conductivity

$$\dot{y}_A = g_A + jb_A, (b_A >> g_A) \tag{1}$$

is comprised of three capacitances (Fig. 1a): exterior capacitance C_H, edge capacitance C_K and internal C_B. The first one depends on dielectric permittivity of the flame and the main sensors application in base on this fact. The second one mostly depends on the temperature. The technical solution previously suggested in [3] permits to make one of these features prevalent. Thereby, on the basis of similar constructions it is possible to create electron density sensor in the combustion chamber volume or temperature sensor in the chamber's wall area.

Sensor's equivalent circuit with built-in antenna (Fig. 1b) represents properties of the microwave diode semiconductor oscillator with antenna [5]. Here $L_p = Z_p / \omega$, $C_p = 1/\omega Z_p$ - equivalent parameters of resonator, Z_p- wave resistance of coaxial length. As opposed to passive resonator with Q-factor Q_p, here Q-factor of electrical circuit is $Q = Q_p / \alpha$, where

$$\alpha = [1 - r_d / (r_n - r_A)] << 1 \tag{2}$$

α -constant component of the diode negative resistance (its reactivity is neglected for now), r_n-resonator loss, $r_A = g_A / (b_A^2 + g_A^2) \approx g_A / b_A^2$. According to [10] let point attention to the well known differential equation and write shorten equations:

$$\frac{1}{X_0} \cdot \frac{dX}{dt} = \frac{d}{dt}(\delta_x) = -\Pi \delta_x - \frac{\omega}{2}(\delta_\partial - \delta_c) + F_1(\upsilon, T_p, E, t)$$

$$\delta\omega = \frac{d\psi}{dt} = -\frac{\omega}{2}\delta_c + F_2(\upsilon, T_p, E, t) \tag{3}$$

where X, ψ - amplitude and phase of oscillation, $\delta_x, \delta_\partial, \delta_c$ - relative increments of amplitude and conductivities (1), $\Pi = \alpha \cdot \Pi_P$- band, which in the theory of oscillations calls strength of the limit cycle, $\Pi_P = \omega / Q_P$, F_1, F_2- functions, which represent in addition to the known factors (nonlinearity of the diode volt-ampere characteristic) vibrations influence, self-radiation, resonator heating and other interferences.

Equation (3) corresponds to isochronous frequency controlled active oscillator: frequency increment $\delta\omega$ (information carrier in monitoring signal) in relative unites is proportional to the capacitance increment with coefficient 0,5 and doesn't depends on amplitude. This is why measuring transform, as a frequency modulation in radio engineering, is noninertial. But this fact is correct only in relation to the electron density.
Fluctuation heating of the edge capacitance, which enters into total circuit capacitance (Fig. 1b), depends on membrane overheating, in which slit is cut through.

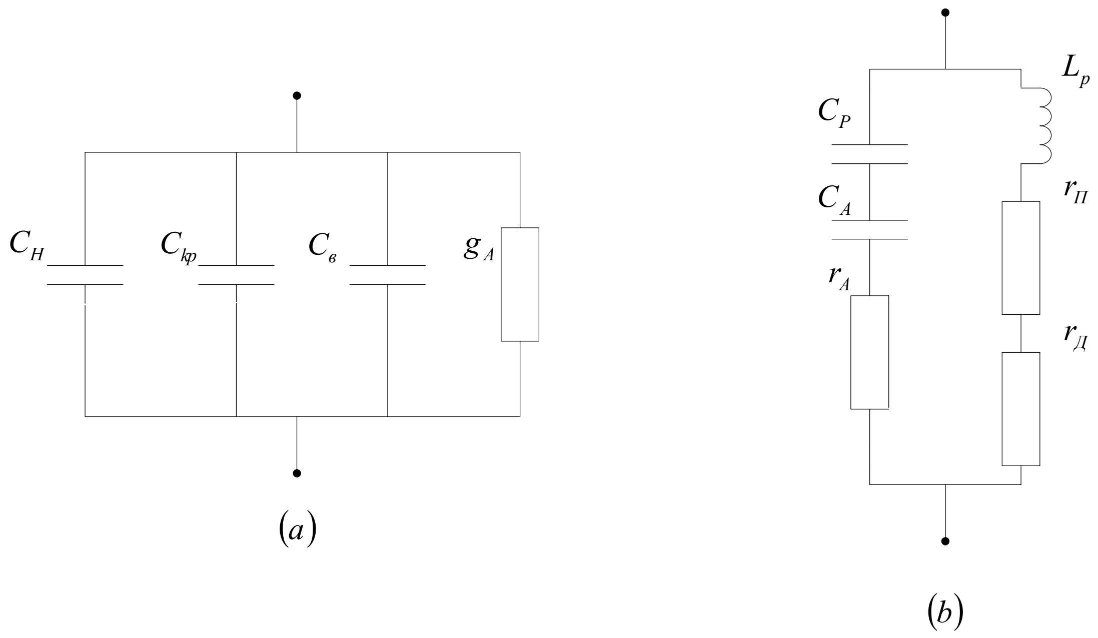

Fig.1. Sensor's equivalent circuit

In accordance with heat-transfer theory, temperature wave attenuation with the frequency is $\Omega_j = 2\pi F_j$ and follows the low, which were revealed by Fourier [9]

$$T(j, y) = T_j \Phi(p_j) \cdot \exp(p_j y), \qquad (4)$$

where $\Phi(p_j) \approx (1 + 2p_j/H)^{-0,5}$, $p_j = \sqrt{\Omega_j/2a}$, $a-$thermal diffusivity, $H-$heat-transfer coefficient (in this case from flame to the fire surface of antenna), T_j $-$wave amplitude in flame. If we specify attenuation in $\sqrt{2}$, we'll receive threshold frequency condition of required band of the temperature response

$$\Pi_T = \Omega_j \le \frac{a}{2\left(\frac{1}{H} + d\right)^2}, \qquad (5)$$

where $d-$ membrane thickness. Numerical example is necessary for explanation. For the copper membrane $a = 10^{-4}\ m^2/\sec$, thickness $d = 0{,}1mm$, threshold frequency $\Omega_j/2\pi \approx 13Hz$ (applicable thermocouples has less than 1Hz). As a result spectral densities of responses of the temperature and concentration sensors are

$$S_{\omega c}(\Omega) \approx \frac{\omega_0^2}{4} \cdot S_N(\Omega),\ S_{\omega T}(\Omega) \approx \frac{\omega_0^2}{4} \cdot \frac{\Pi_T^2}{\Pi_T^2 + \Omega^2} \cdot S_T(\Omega). \qquad (6)$$

Thereby this circuit and constructive solution can be used not only for concentration sensor, but also as high-speed thermal sensor.
When measuring concentration, monitoring signal independence from the temperature provides either by thermo compensation or by simple membrane thickening. When measuring temperature independence from N provides by probe frequency selection, because exterior capacitance C_H dependence from plasma dielectric permittivity is inverse to ω^2.
Let's return to equation (3) and to interferences, represented by the set of functions F_1 and F_2. Resonator heating has been researched in [6, 12], here the response is weak and its spectrum is quite narrow-band (less than 1Hz). Radioelectronic equipment protection from vibrations is a long-standing task; in this application its solution is available for engineers. This is why let's focus on self-radiation. It is close by behavior to the white delta-correlated noise with spectrum S_0.
Due to [10] let's extract in-phase and quadrature components $E_1(t)$, $E_2(t)$ and substitute them into equation (3) instead of functions F_1 and F_2. In relation to currents, induced by external radio radiation in a band Π, active oscillator is similar to receiver with associated heterodyne.
Here in the frequency transformation an effect, which is analogous to detection, is essential. Its low-frequency products penetrate through power filter with band Π_Φ and cause small changes of diode operating point, its capacitance and some anisochronism of active oscillator. Self-bias circuit plays a certain role here. Let's estimate specified effects by coefficients K_∂ and K_c.
Spectral densities of the frequency and amplitudes responses are

$$S_\omega(\Omega) = \left\{ \frac{K_c^2}{\Pi_\Phi^2 + \Omega^2} \cdot \left[\frac{\Pi_P^2}{\Pi_p^2 + \Omega^2} \right] \right\} \cdot S_0 ,$$

(7)

$$S_x(\Omega) = \left\{ \frac{1}{4} \cdot \frac{K_\partial^2}{(\Pi_\Phi^2 + \Omega^2) \cdot \left(\Pi^2 + \Omega^2\right)} \right\} \cdot S_0 .$$

$\Pi_\Phi << \Pi$, because of this its influence is more essential. This is why created by self-radiation interference effect is more significant on the lowest frequencies.

Analysis of an autodyne sensor's dynamics

In the sensor with remote antenna we are interested in parameters, which are connected with reflection coefficient from antenna

$$\dot{\Gamma}_A = \left|\Gamma(b_A, g_A)\right| \cdot \exp\left[j\eta(b_A, g_A)\right]. \qquad (8)$$

In this case regular components, appropriate to the nominal conditions of TPE, determine sensor's sensitivity and autodyne response band, while random components determine its spectrum. As in a first case, it is possible to monitor either N, or T.
Reduced autodyne equations are:

$$\frac{1}{\chi_0} \cdot \frac{d\chi}{dt} = \frac{d}{dt}\delta_x = -\Pi\delta_x + \Pi_a \cos\eta \cdot \delta_a + \Pi_a \sin\eta \cdot \delta_\eta + F_3(t)$$

(9)

$$\delta\omega = \frac{d\psi}{dt} = -\Pi_a \sin\eta \cdot \delta_a - \Pi_a \cos\eta \cdot d\eta + F_4(t),$$

where $\Pi_a = \Pi|\Gamma|, \delta_a, \delta_\eta$ - relative increments of amplitude and phase of reflection, $F_{3,4}(t)$-functions, which are similar to (3).

Spectral density of the frequency response is

$$S_\omega(\Omega) = \frac{\omega^2}{4} \cdot \frac{\Pi_c^2}{\Pi_c^2 + \Omega^2} \cdot S_\eta(\Omega) + \frac{1}{4} \cdot \frac{\Pi^2}{\Pi^2 + \Omega^2} \cdot \frac{\Pi_S^2}{\Pi_S^2 + \Omega^2} \cdot S_\Gamma(\Omega) , \qquad (10)$$

where $\Pi_c = \Pi_a \cos\eta$, $\Pi_S = \Pi_a \sin\eta$; $S_\eta(\Omega)$, $S_\Gamma(\Omega)$-linear function of the spectral densities $S_N(\Omega)$ or $S_T(\Omega)$.

Sensor with remote antenna (autodyne sensor) is less subjected to the heating (except antenna) and better than the first type sensor protected from vibrations. This is why we'll confine again by estimation of the self-radiation interference influence.

Following our approach, let's find spectral densities value in quasi-isochronous approximation:

$$S_\omega(\Omega) \approx \frac{\omega_0^2 \Omega^2}{4\chi_0 \left(\Pi_C^2 + \Omega^2\right)} \cdot S_\eta(\Omega),$$

$$S_x(\Omega) \approx \frac{\Pi^2 \cdot \Omega^2}{4\chi_0 \left(\Pi^2 + \Omega^2\right) \cdot \left(\Pi_S^2 + \Omega^2\right)} \cdot S_\Gamma(\Omega). \qquad (11)$$

There are two distinctions from the first type sensor: interference effect decreases with an autooscillation amplitude growth and this interference effect is suppressed on the low frequencies. The last is typical for the autodynes and synchronized active oscillators, which have similar behaviour.

Discussion

Shown above the significant advantage of active oscillating sensor by sensitivity has been experimentally proved [11]. Active oscillator advantage over autodyne by modulating frequencies band is well known.

To be more accurate let's do some careful estimations, limiting by probe frequencies range in experiments: $f = (2...4) \cdot 10^9\,Hz$, $\Pi_p \sim 10^8\,Hz$, $\Pi > 10^6\,Hz$, $\Pi_C < 10^5\,Hz$, $\Pi_S < 10^4\,Hz$, $\Pi_\Phi \sim (10^2...10^4)Hz$, $\Pi_T < 10^2\,Hz$, $\Pi_M < 10\,Hz$ (all values are given in translation to the cyclic frequency).

The last value Π_M inverse to the time constant of actuator in automatic control system of TPE modes, in which our sensors are belong also. It is clear, that this value and antenna's properties for our termosensors determine our conclusions. Pictures 3a,b, which are given in relative scales (on pic.2a it is much smaller), permit us to compare the revealed effects- amplitude-frequency characteristics of the sensors and frequency bands of the monitoring signal components.

<u>Active oscillating sensor (Fig 2a) and autodyne sensor (Fig 2b):</u>

1- monitoring signal of the thermosensor (red curve);
2- power supply filter and converted plasma self radiation (blue curve);
3- resonator and additive plasma self radiation (green curve);
4- monitoring signal of concentration sensor (violet curve);
5- resonator heating (yellow hatching).

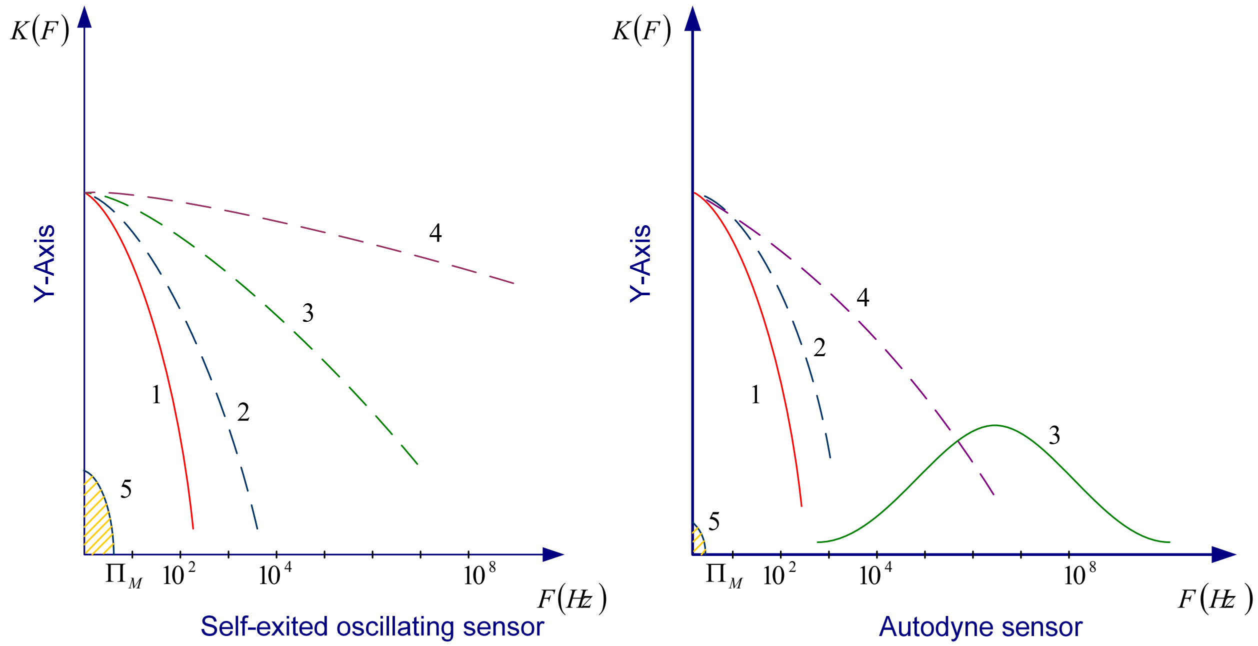

Fig (2a, b). Normalized frequency characteristics of responses

Conclusions

In spite of lesser sensitivity, but because of suppress of flame self-radiation influence, as well as better thermo- and vibra-protection [13], autodyne sensor is more preferable.

References

[1] V.E. Zarko, K.K. Kuo, "Critical review of methods for regression rate measurements of condensed phase system," Nonintrusive Combustion diagnostics,K.K. Kuo and T.Parr, Eds. New York: Begel House, pp. 600-623, 1994.

[2] Patent Rus.№2374559 C1, E.Safonova, V.Boloznev and others, in press, 27.11.2009, №33.

[3] E. Safonova "Minimization of an autodyne sensor's error, stipulated by the antenna's heating", Proc. EFTF 14th., pp. 241-245, Turin, Italy, March 2000.

[4] E. Safonova, V. Boloznev, "Autodyne microwave sensor of combustion process: behavior under fast heating", proc. EFTF15th, pp.88, Neuchatel, Switzerland, 2001.

[5] V. Boloznev, A. Chabdarov , "Sensor of dielectric permittivity of the ionized gas flow" Transl. Instruments and experimental technique, №6,1992.

[6] V. Boloznev, E. Safonova, "Diode microwave active oscillator with a multi-link resonator," Proc. International Symposium on Acoustoelectronics, Frequency control and Signal generation, pp. 139-143, St.Petersburg, Russia, June, 1998.

[7] I. Prigojin, S. Kondrapudi, "Modern thermodynamics", M: Mir, 2002.

[8] K. Kurokava, "Some basic characteristics of broadband negative circuits", B.S.T.Y., №6, 1969.

[9] S. Kutateladze, V. Borishansky, "Heat transfer reference book", A.M.: Gosenergoizdat.

[10] A. Malakhov, "Fluctuations in self-oscillating systems", M.:Nauka.

[11] E. Safonova, V. Boloznev, V. Dakhin, "Experimental estimation of functional capabilities and temperature error of microwave sensors of combustion process", Proc. of the 18th EFTF, Surrey, UK, April, 2004.

[12] E. Safonova, V. Boloznev, "Microwave oscillator as a sensor of electrophysics flow parameters", Proc. Joint meeting of the 13th European frequency and time forum and 1999 IEEE international frequency control symposium, pp. 1062-1066, Besancon, France, 1999.

[13] Safonova, V. Boloznev, F. Sultanov, M. Stanchenkov, F.Mirsaitov, "Autodyne microwave thermosensor under vibrodisturbance influence", Proc. of the 20th EFTF", Braunschweig, Germany, 2006.