IDENTIFICATION OF SPURIOUS PEAKS AT THE UHF REFLECTOMETRY OF PLASMA PRODUCED BY HF METHOD

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Using computer modeling, we have established an analytical dependence of the actual signal frequency, F_X, on the frequency of a spurious signal, $F_{\rm obs}$, which arises in the processing of experimental data due to the manifestation of the known phenomenon "disguise of frequencies". The method of authentication of spurious peaks is suggested. The efficiency of the method was confirmed in the real experiment when investigating the dynamical characteristics of harmonics of an HF generator used for producing and heating a plasma in the stellarator-type fusion device U-3M. The results can be applied also to the future experiments on the production and heating of an HF plasma in the U-2M torsatron.

1. Introduction

In researches on the controlled thermonuclear fusion, a noticeable attention is devoted to the study of fluctuations of plasma parameters – electron density, electron temperature, and plasma potential [1]. In these investigations, a main technique is the recording of signals carrying the information about fluctuations and the study of the fluctuation parameters – spectra and auto- and cross-correlation functions by the digital methods of analysis.

The spectral characteristics of fluctuations are mostly determined by the method of fast Fourier transformation (FFT). By the FFT method, the available width of a uniquely interpreted spectrum is defined by the sampling rate f_S of an analog-digital converter (ADC) used in the system of signal recording. A maximum width of the uniquely interpreted spectrum is equal to the Nyquist frequency $F_{\rm N} = 0.5\ f_S$. For experiments on the $l = 3$ torsatron "U-3M", ADC with a maximum frequency $f_S = 2.8$ MHz were used, which allowed one to study the spectra of signals in the frequency band of 0–1.4 MHz. At the same time, during experiments on the torsatron "U-3M", the plasma is produced and heated by RF oscillations with the frequency $f = 7 \div 9$ MHz. It is of interest to study the plasma parameter fluctuations about the frequencies of RF oscillations being excited, as well as, about the close frequencies of the ion-cyclotron resonance, 10–11 MHz, depending on the specific value of the magnetic plasma confining field.

Investigations of the plasma electron density fluctuations in U-3M were carried out with the use of microwave reflectometers [1]. The spatial correlation was determined by means at least of 2 channels. Therefore, the fluctuation spectrum was narrowed into the region of 0–0.7 MHz due to a decrease in f_S. The analysis of plasma density fluctuation spectra by the FFT method revealed the narrow-band oscillations (peaks) [2] with frequencies differing both from the wide-band spectra of the low-frequency turbulence observed ($f = 0 \div 100$ kHz) [3–5] and from ion-cyclotron resonance frequencies [6]. It was supposed that these oscillations are a manifestation of the known phenomenon of a disguise of frequencies, which arises up at the signal conversion from an analog form in a discrete one, when the frequency of sampling of an in-use ADC is less than the frequency of the explored signal [7]. In such cases, it is recommended to use analog filters in the experiments [7–9]. However, there is no universal method to clear spectra, which could be used without a preliminary analysis of parameters of a spurious noise signal [8].

In Fig. 1, three frequency peaks with $F_{\rm obs1}= 194.8$ kHz, $F_{\rm obs2} = 389.6$ kHz, and $F_{\rm obs3} = 584.4$ kHz obtained after the spectral analysis of reflectometry signals are clearly seen. Below, it will be shown that these frequencies are a result of the above-mentioned phenomenon of a disguise of frequencies and, in reality, are the first three harmonics of a RF generator used for the production and heating of plasma: $F_{X1} = 8766.22$ kHz, $F_{X2}= 17532.44$ kHz, and $F_{X3}= 26298.66$ kHz, respectively [2].

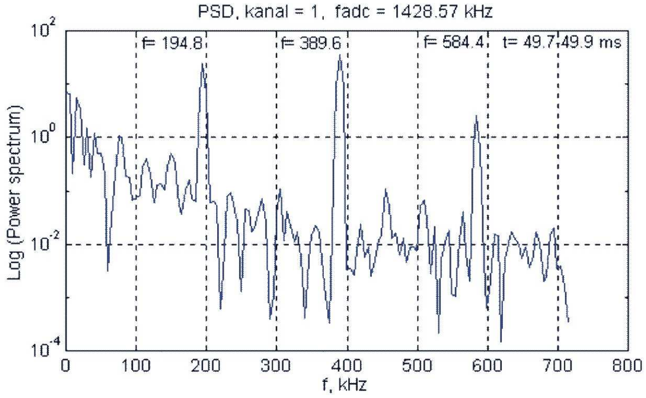

Fig. 1. Power spectrum density (PSD) of fluctuations of a reflectometry signal

2. Numerical Simulation and Discussion

The goal of the present work is to study the possibility of defining the true value of the frequency of a signal F_X by the frequency of its "track" $F_{\rm obs}$ obtained after the FFT processing of a signal at the ADC exit when its sampling rate f_S is much lower than F_X. The problem was solved by the numerical simulation of the digitization process for the monochromatic signals with frequencies exceeding the Nyquist frequency. For the analysis of signals, the FFT method was applied. As monochromatic oscillations, a sinusoid was taken with the frequency F_X = 11 MHz which was significantly higher than the ADC sampling rate f_S = 2.8 MHz. Consequently, it is known *a priori* that the frequency $F_{\rm obs}$ obtained in the signal spectrum after the FFT processing of an ADC signal is *a fortiori* false (above we named it as a "track" of the true frequency of the input signal F_X). By simulating the process of ADC digitization of frequencies F_X (f_S = 2.8 MHz) within 0–12 MHz, the dependence of the frequency $F_{\rm obs}$ on the frequency $F_X$was plotted (Fig. 2,*a*). To reach a high accuracy when plotting the function $F_{\rm obs} = f(F_X)$, the calculations were carried out with a step of 10 kHz for the frequency F_X. From Fig. 2,*a*, it follows that the direct linear relation is valid to the value of $F_X = 0.5 f_S$, i.e. the maximum of the direct linear relation is limited by the Nyquist frequency $F_N = 0.5\ f_S$. As the frequency F_X further increases, the inverse linear relation for $F_{\rm obs}$ is observed, i.e. $F_{\rm obs}$ linearly decreases to the minimum value $F_{\rm obs} = 0$ at $F_X = f_S$= 2.8 MHz. During the further increase in F_X to 12 MHz, the dependence behaves similarly – the maxima are limited by the Nyquist frequency (in the case under consideration, $F_{\rm N}$ = 1400 kHz). Zero values of $F_{\rm obs}$ take place at $F_X = nf_S$, where n = 0, 1, 2, 3... (integer number). The n value properly means how much times the frequency F_X exceeds the ADC sampling rate f_S. The limiting value $n = 0$ means that, in this case, $F_X\ /\ f_S < 1$. For the initial frequency of the sinusoid with F_X = 11 MHz, its "track" (for f_S= 2.8 MHz) is $F_{\rm obs}$ = 199.6 kHz. From Fig. 2,*a*, it follows that 9 different frequencies F_X correspond to the frequency $F_{\rm obs}$ = 199.6 kHz. By repeating the FFT procedure for the sampling rates f_S= 2.5 MHz and f_S= 2.3 MHz at the same sinusoid frequency F_X = 11 MHz, we obtained another set of frequencies $F_{\rm obs}$ with a similar behavior of the $F_{\rm obs} = f\ (F_X)$ function (Fig. 2,*b* and Fig. 2,*c*, respectively).

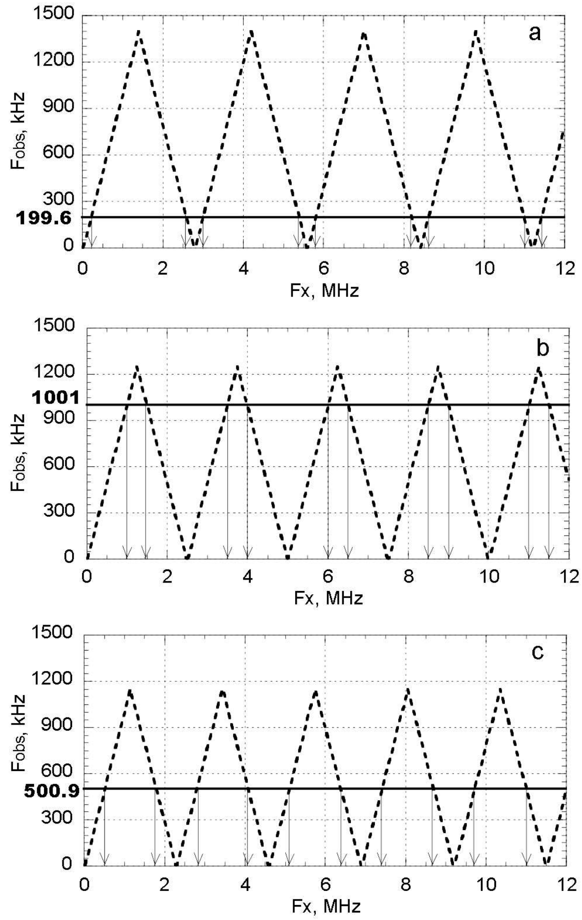

Fig. 2. Frequency $F_{\rm obs}$ versus the sine wave oscillation frequencyF_X for three values of the signal sampling rate f_S, MHz: *a* – 2.8; *b* – 2.5; and *c* – 2.3

In order that the relation between F_X and $F_{\rm obs}$ be established more evidently, in the next numerical experiment, the FFT procedure has been carried out for the fixed sampling rate f_S= 0.7 MHz. Then the frequency F_X was changed from $F_{X\,\min} = 10.5$ MHz to $F_{X\,\max} = 11.2$ MHz, i.e. $\Delta F_X = f_S = 0.7$ MHz. The results of these calculations are given in Table 1. For seven values of F_X in this frequency range, we calculated $F_{\rm obs}$ and the ratio F_X/f_S. In the general case, it is possible to determine $F_X/f_S = n + l$, where n is named above as an integer number and l is a fractional number ($0 \le l \le 1$). The limiting value l= 0 means that F_X is many times higher than f_S, and the limiting value l= 1 implies that, in fact, l= 0 in this case, and n is increased by 1, i.e. it becomes $(n + 1)$. From Table 1, it follows that

$$F_X = nf_S + lf_S = nf_S + F_{\rm obs}. \qquad (1)$$

If l= 0, then $F_X = nf_S$. As l increases from 0 to 0.5 then the frequency$F_{\rm obs}$ increases to the maximum value being determined by the Nyquist frequency $F_{\rm obs} = 0.5$ f_S. Therefore, Eq. (1) is valid only for $0 \le l \le 0.5$, i.e. for the data of the upper part of Table 1. At $F_X = 10.88$ MHz, $F_X\ /f_S$= 15.543, i.e. n = 15 and l = 0.543. In this case according to (1), $F_{\rm obs} = lf_S$ = 380 kHz. This, first, contradicts to the Nyquist theorem, and, second, the last value is higher than the estimated value $F_{\rm obs}$ = 320 kHz. For $0.5 \le l \le 1$, the relation between the given frequency of the sinusoid F_X and its "track" $F_{\rm obs}$ has the following form (according to the data of the lower part of Table 1):

$$F_X = (n+1)f_S + (l-1)f_S = (n+1)f_S - F_{\rm obs}. \qquad (2)$$

Thus, Eq. (1) satisfies the direct linear relation $F_{\rm obs} = f(F_X)$, and Eq. (2) satisfies the inverse linear relation $F_{\rm obs} = -f(F_X)$.

So, the general equation describing this process has the following form

$$F_X = nf_S \pm F_{\rm obs}. \qquad (3)$$

However, to estimate F_X, it is necessary to determine the value of n and the sign (+) or (–) in Eq. (3). One of the possibilities to overcome this difficulty is the use of three ADCs with different sampling rates f_S in order to perform the simultaneous recording of a signal at the single frequency F_X. Another possibility for the unique estimation of the frequency F_X may be the estimation of three values of $F_{\rm obs}$ for the same frequency F_X but at three values of f_S (Fig. 2). The estimated values of F_X and n and the sign for every value of f_S and $F_{\rm obs}$ from the data of Fig. 2,*a,b,c* are given in Table 2. As is seen from Table 2, the most often repeated frequency is the frequency F_X = 11 MHz that corresponds to the real frequency arbitrarily selected for the model calculations.

Furthermore, for the unique determination of F_X, the values of f_S should be aliquant to each other to exclude the coincidence of frequencies. If a sought frequency is the time function, its time variation also can be determined. For this purpose, the FFT procedure is carried out sequentially in the required temporary windows. Then the mean F_X value is determined during this time interval Δt similarly to the case of F_X = const. Just so we have obtained the values of frequency changes in the first three harmonics of a RF generator during the plasma discharge in U-3M [10].

The data on the time variation of harmonic frequencies (F_X, with X=1, 2, 3) in the process of discharge in the U-3M are presented in Fig. 3. As seen from the plots, the harmonic frequencies at the stage of the plasma initiation (4–8 ms) remain practically unchanged. With the occurrence of a breakdown (8th ms), the harmonic frequencies abruptly increase up to their maximum values (11th ms) and then start to fall down, first, quickly up to the 15th ms and very slowly after the 15th ms. The time variation of harmonic frequencies during the discharge is very much similar to the behavior of the plasma density up to the moment of the RF pulse switch-off (see Fig. 2,*c* [2]). A special point in the plot of the first harmonic (Fig. 3,*a*) marks the frequency f_1 =8768 kHz of a HF generator measured

T a b l e 1. Results of numerical simulation: values of the frequencies $F_{\rm obs}$ obtained by the insignificant change in the sine wave frequency F_X at the same sampling rate f_S = 0.7 MHz

N	F_X,MHz	f_S, MHz	F_X/f_S	n	l	$F_{\rm obs}$, MHz
1	10.50	0.7	15	15	0.0	0.0
2	10.51	0.7	15.014	15	0.014	0.010
3	10.61	0.7	15.157	15	0.157	0.110
4	10.85	0.7	15.500	15	0.500	0.350
5	10.88	0.7	15.543	15	0.543	0.320
6	11.05	0.7	15.786	15	0.786	0.150
7	11.2	0.7	16	15	1.0	0.0

T a b l e 2. Results of a numerical simulation using the information obtained from Fig. 2,$a-c$ for three values of the sampling rate f_S

F_X, MHz (f_S =2.8 MHz)	F_X, MHz (f_S =2.5 MHz)	F_X, MHz (f_S =2.3 MHz)	n	Sign
0.1996	1.001	0.501	0	+
2.6004	1.499	1.799	1	–
2.9996	3.501	2.801	1	+
5.4004	3.999	4.099	2	–
5.7996	6.001	5.101	2	+
8.2004	6.499	6.399	3	–
8.5996	8.501	7.401	3	+
11.0004	8.999	8.699	4	–
11.3996	**11.001**	9.701	4	+
13.8004	11.499	**10.999**	5	–

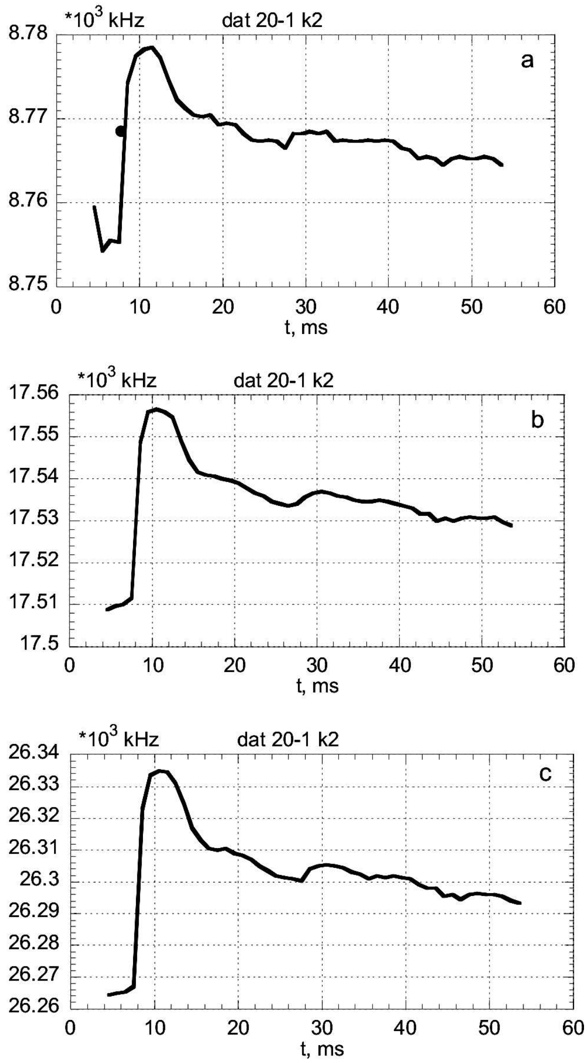

Fig. 3. Behavior of HF generator harmonic frequencies during discharge

independently by a cymometer; the value is close to the average frequency of the first harmonic during the discharge.

The deviation of generator oscillations from harmonic ones can be due to the formation of a space-charge layer with nonlinear capacitance near the HF antenna [11]. The possibility of the generation of harmonics by an external HF generator has been confirmed in numerical model experiments [2]. A nonlinearity of the current-voltage characteristic of a near-antenna space-charge layer can cause the time variation (Fig. 3) of the frequencies of HF generator harmonics during the plasma discharge [12]. Note that the plots for the second and third harmonics were obtained from the experiments rather than by a simple doubling and tripling of the fundamental frequency.

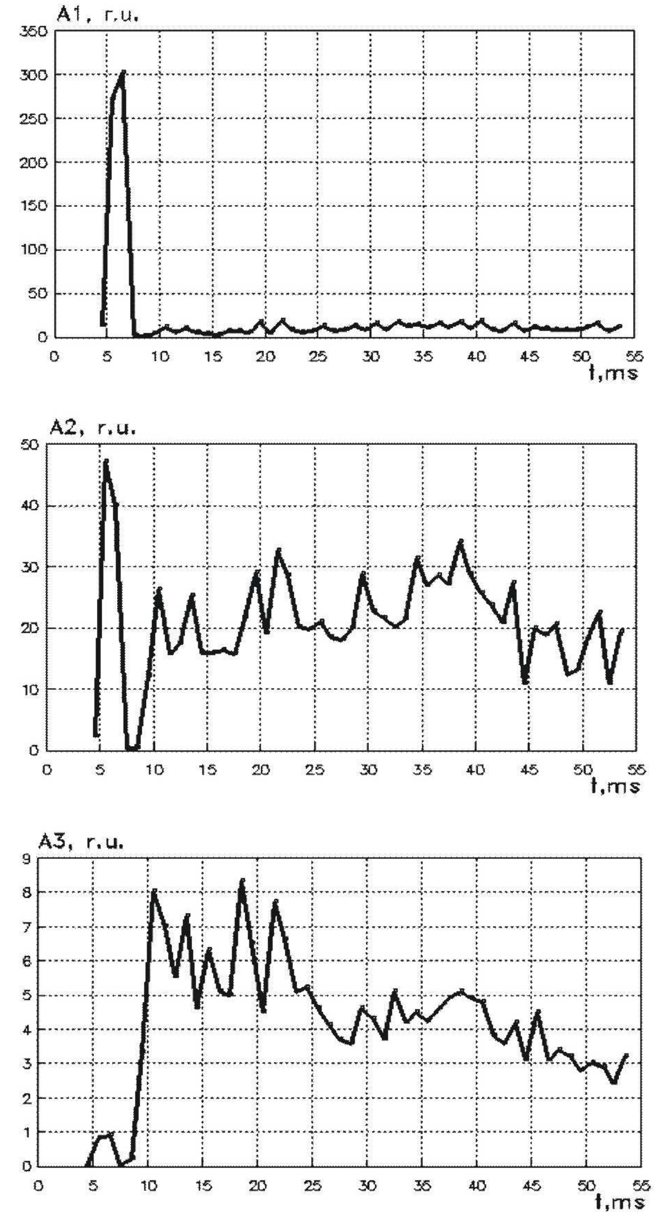

Fig. 4. Behavior of HF generator harmonic amplitudes during the discharge

With a two-fold increase in the sampling rate f_S of the ADC, the occurrence of seven harmonics was observed. However, three first harmonics were of the highest amplitudes. From the sequence of the PSDs calculated for every millisecond of a HF pulse, the amplitudes at each of three harmonics were calculated (Fig. 4).

With the onset of a HF pulse at the 4th ms, the amplitude of the first harmonic increases very quickly. Before reaching its maximum value, the rate of increase in the amplitude somewhat decreases. At the sixth millisecond, the amplitude reaches its maximum and then (8th ms) likewise quickly falls down. Approximately from this time forth, the amplitude remains practically unchanged throughout a HF pulse, showing only small fluctuations. This behavior of the first-harmonic RF field amplitudes is in a qualitative agreement with the classical description of the process of HF discharge initiation [13]. Between the 4th and 6th milliseconds, close to the antenna, the avalanche ionization of the gas due to the electric field of an antenna-radiated HF wave occurs. At the peak value of the amplitude (6th ms), the gas breakdown throughout the torus occurs, and a toroidal plasma column is eventually formed by the 8th ms. The time duration of the discharge initiation is in good agreement with the results of [14], where optimum conditions of the starting phase of the HF discharge in the U-3M were studied in relation to the working gas pressure and the HF voltage applied to the antenna. It is seen from Fig. 4 that the stage of discharge initiation can be clearly traced at the second and third harmonics, as well. However, their amplitudes are substantially lower than the 1^{st} harmonic amplitude. The relationship of the amplitudes of three first harmonics during the evolution of the discharge is shown in Fig. 5. The data of the figure demonstrate that, at the breakdown phase, the first harmonic is of the highest amplitude; but, to the end of the discharge, its amplitude becomes the minimal one.

The dynamics of the HF generator frequency and the amplitudes of harmonics can be useful when studying the conditions of the initial gas breakdown and the subsequent plasma heating.

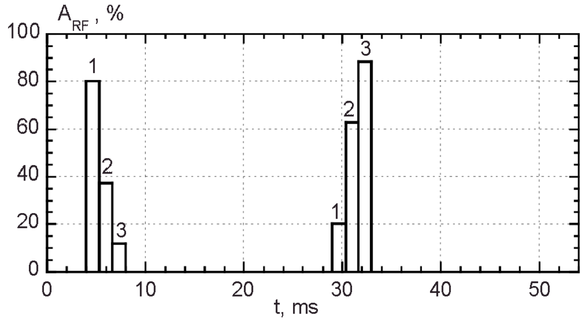

Fig. 5. Distribution of averaged harmonic amplitudes at the breakdown stages (4 to 9 ms) and at the quasistationary stage of the discharge (9 to 54 ms)

3. Conclusion

To summarize, we note that the method can be applied to the determination of the real frequencies of plasma oscillations with a frequency significantly exceeding the ADC sampling rate. This method is not limited by a value of F_X; therefore, it can be used for any experiments providing that $F_X/f_S \gg 1$, as well as, for the measurement of the frequency variation during the physical process. For the study of low-frequency signals ($F_X/f_S < 1$), the method of frequency determination may be important for the identification of the induced noise with frequencies $F_X/f_S \gg 1$.

The behavior of frequencies and amplitudes of three first harmonics of the HF field used for the plasma production and heating in the U-3M torsatron has been determined. The dynamics of the harmonics of the frequency and amplitude of a HF generator can be useful in studying the conditions of the initial gas HF breakdown and the subsequent plasma heating in the U-2M torsatron.

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ІДЕНТИФІКАЦІЯ ПАРАЗИТНИХ ПІКІВ ПРИ НВЧ-РЕФЛЕКТОМЕТРІЇ ПЛАЗМИ, СТВОРЮВАНОЇ ВЧ-МЕТОДОМ

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Р е з ю м е

За допомогою комп'ютерного моделювання встановлено аналітичну залежність частоти реального сигналу F_X від частоти паразитного сигналу F_{obs}, який виникає в процесі обробки експериментальних даних внаслідок явища "маскування частот". Запропоновано метод ідентифікації паразитних піків. Ефективність методу підтверджена в реальному експерименті з дослідження динамічних характеристик гармонік ВЧ-генератора, який використовується для створення і нагрівання плазми в установці стелараторного типу У-3М. Одержані результати можуть бути використані при ВЧ-створенні і нагріванні плазми у торсатроні У-2М.