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INVESTIGATION OF SONOLUMINESCENCE AMPLIFICATION UNDER THE INTERACTION OF ULTRASONIC FIELDS WIDELY DIFFERING IN FREQUENCY

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The laws of sonoluminescence generation under the interaction of ultrasonic fields widely differing in frequency have been investigated. It is shown that nonadditive amplification of the sonoluminescence is observed not only under the simultaneous action of the fields on a liquid, but also in a high-frequency field after preliminary insonification of the liquid by a low-frequency field. The phenomenon of a long-duration aftereffect of the low-frequency field on the cavitation generated by the high-frequency field has been revealed. On the basis of the obtained results the conclusion has been drawn that the main mechanism of increasing the cavitation activity in the interacting fields is the generation of new cavitation nuclei as a result of the collapse of bubbles excited by the low-frequency field.

Sonoluminescence (SL) is the generation of luminescence in liquids under the action of powerful ultrasound. It is well known that it has a cavitation feature and is associated with the formation and collapse of microcavities (bubbles) in a liquid [1–6]. In the last few years, a method for confining a solitary (levitating) bubble in a standing wave field has been developed [7]. This method has made it possible to reveal a number of extraordinary and new laws of SL [8–10]. Experiments with solitary bubbles validated the thermal theory of SL according to which luminescence is caused by a strong gas heating inside the bubble as a result of its adiabatic compression (collapse) or upon the formation of a spherical convergent shock wave in it [7–9]. On the basis of the analysis of the SL spectra it has been concluded that in the case of single-bubble SL (SBSL), the vapor-gas mixture in the bubble can be heated to $T = (3–5)\cdot 10^4$ K [8] and the corresponding maximum pressures reach 10^5 atm.

Each burst of SL includes up to 10^6 photons at room temperature at a frequency of 20 kHz and the degree of energy concentration at a bubble collapse is 10^{11} to 10^{12} [8].

Theoretical estimates show that higher temperatures can also be attained under the condition of a spherically symmetric collapse and spherical symmetry of the shock wave formed thereby [11, 12]. Under such conditions, new physicochemical processes in the liquid and high-energy reactions are possible [6, 11–14]. In [15], data pointing to the probability of a nuclear fusion reaction are presented.

However, under the conditions of multibubble SL (MBSL) such high parameters have not been attained as yet. The maximum temperatures are estimated to be equal to $(2–6)\cdot 10^6$ K, [16, 17], and, accordingly, the pressures are also an order of magnitude smaller than in the case of SBSL. The number of photons in the pulse does not exceed 10^4 [18, 19]. Moreover, the SBSL and MBSL spectra differ [8, 16, 20]. Taking into account the difference in parameters between the single-bubble and multibubble SL, in [6] the hypothesis that the mechanisms of luminescence generation for these types of cavitation can be different was set up. In [2, 14, 20, 21], an electrical theory of SL was proposed and developed, and in [6] it was emphasized that in the case of single-bubble cavitation the nature of SL is thermal and in the case of multibubble SL electrical. Recently [22], in experiments with xenon-saturated water at large ultrasound intensities for MBSL, spectra analogous to SBSL have been obtained. This leads to the conclusion that the mechanism of SL in both cases is one and the same (i.e., thermal), and the difference is only in temperatures and pressures attainable in bubbles at a collapse [22].

From the foregoing it is clear that there are considerable possibilities for increasing the conversion efficiency and concentration of energy in MBSL. If one could manage to bring the temperatures and pressures attainable at a col-

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lapse of bubbles in the MBSL composition close to the corresponding SBSL parameters, one could expect significant progress in the field of investigating the cavitation, extending the field of application of ultrasound, and increasing the efficiency of a number of technologies [23].

In [24–26], it is shown that the action of a low-frequency (LF) field on the cavitation region generated by a high-frequency (HF) field is an effective method for increasing the cavitation activity. In particular, in interacting LF and HF fields a nonadditive amplification of sonoluminescence has been observed. If a pulse-modulated HF field is used, then the SL intensity in the combined field created by simultaneously operating HF and LF radiators is many times the sum of the SL intensities generated when each radiator operates separately [25, 26].

An increase in the total energy introduced into the liquid during the operation of two radiators and the field interference are apparent causes of the increase in the SL luminescence. We also consider in more detail other possible mechanisms.

1. If the frequency of the LF field is much lower than the frequency of the HF field, then the LF field is quasi-static with respect to the HF field [26]. During the vacuum half-cycles of the LF field the quasi-static pressure $P_\Sigma = P_0 + P_{LF}$ decreases. Before the action of the LF field the pressure in the microbubbles-cavitation nuclei is balanced with the hydrostatic pressure P_0 and the surface tension pressure $2\sigma/R$. In the negative half-cycle of the LF field ($P_{LF} < 0$), the total quasi-static pressure decreases and can even be negative (if $|P_{LF}| > P_0$). Therefore, cavitation nuclei grow to larger sizes and the cavitation threshold decreases. As a result, the number of bubbles cavitating under the action of the HF field increases. In the compression half-cycle of the LF field ($P_{LF} > 0$), a higher quasi-static pressure, in accordance with [27–29], favors a faster collapse of the bubbles that have formed during the vacuum half-cycle of the LF field. As a result, the pressures and temperatures attained inside the bubbles will increase, which can cause an increase in the SL intensity.

2. One of the main causes of the decrease in the efficiency of energy concentration by the bubbles in the composition of the cavitation region compared to the single-bubble cavitation is thought to be their action on one another by means of the shock waves or due to the hydrodynamic forces [5, 16, 23]. As a result of such interactions, the bubbles may be deformed. And because their spherical form is unstable under collapse [5, 28, 30], any deformation will grow at a high rate. The nonspherical collapse cannot provide such a high degree of energy concentration as the spherical collapse does [31]. What is more, at a rapid development of instabilities the bubble will break down into parts at an early stage of collapse. In this case, any significant compression of the vapor-gas mixture inside it cannot be attained. Bubbles in the composition of stable formations — clusters — interact most strongly [5, 32, 33]. Therefore, the clusterization can be one of the main causes of the decrease in the integrated intensity of cavitation with increasing concentration of liquid bubbles. Probably, large cavities generated by the LF field produce a strong effect on the clusters of HF bubbles, impeding their formation and increasing the homogeneity of their distribution over the volume of the cavitation region. Because of this better conditions for a more effective collapse of cavities in the HF field can be provided.

3. The cavitating liquid is an essentially nonlinear medium. Under the interaction of fields with frequencies f_{HF} and f_{LF} combination frequencies $f_{LF} + f_{HF}$ and $f_{HF} - f_{LF}$ are generated in it [34]. The same also holds true for harmonics of f_{LF} and f_{HF} fields. Therefore, in the spectrum of the resulting field a wider set of frequencies can be present than in the simple sum of the spectra of the initial fields. This should lead to a widening of the range of sizes of the bubbles involved in the cavitation process, and, consequently, to an increase in the total number of cavitating bubbles as well [25].

4. As is known [2, 5, 35, 36], cavitating bubbles upon collapse break down into small parts. The number of thus-obtained fragments, i.e., smaller bubbles, can reach 40 [35]. Their size is obviously much smaller than the size of the initial bubble. Therefore, fragments of a bubble collapsed under the action of the LF field can be suitable nuclei for cavitation in the HF field. Since the new nuclei contain much less air than the initial bubbles steadily existing in the liquid, they collapse in the HF field at a higher rate. Thus, due to the action of the LF field on the liquid, the number of bubbles cavitating in the HF field considerably increases and, moreover, the rate of collapse is likely to increase [24, 26]. This should lead to an increase in the maximum pressures and temperatures attained in the vapor-gas mixture inside the bubbles and, as a consequence, to an increase in the SL intensity.

The results of the investigations presented below permit estimating the role of the above-mentioned mechanisms in the effect of SL amplification under the interaction of ultrasonic fields widely differing in frequency.

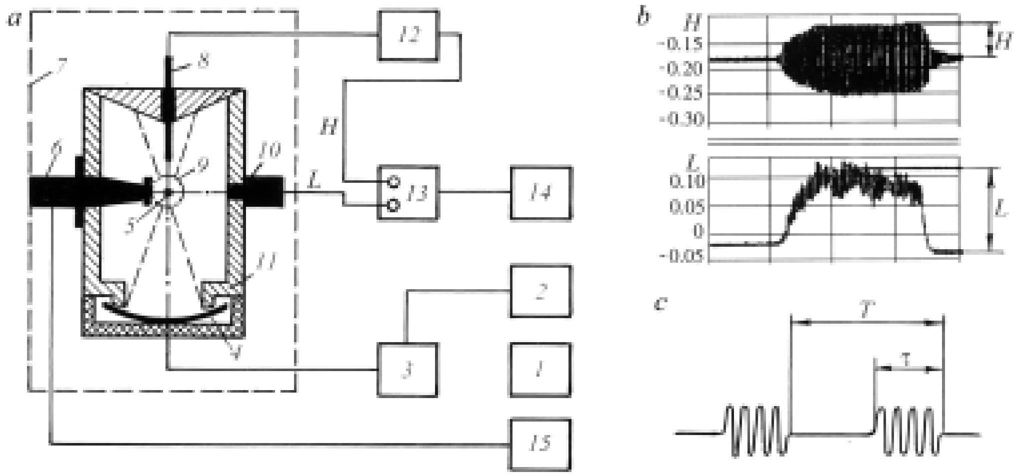

Fig. 1. Diagram of the experimental facility: (1, HF generator of a.c. voltage; 2, pulse generator; 3, mixer; 4, HF radiator; 5, focal spot of the HF radiator; 6, LF converter; 7, light-tight duct; 8, hydrophone; 9, visual field of the photomultiplier; 10, photomultiplier; 11, working vessel; 12, preamplifier; 13, storage oscilloscope; 14, computer; 15, LF generator of a.c. voltage) — a; example of hydrophone signal *H* recording (upper oscillogram) and sonoluminescence signal recording (lower oscillogram) — b; controlling signal shape — c.

Facility and Methods. The working vessel of the facility is made in the form of a cylinder from stainless steel with hollow water-cooled walls of internal diameter 120 mm and length 180 mm (Fig. 1a).

A high-frequency piezoceramic focusing radiator 4 of diameter 65 mm is mounted through a hole in the vessel bottom by means of a PTFE cap screwed on the vessel. The resonant frequency of the HF radiator is 880 kHz. At the level of its focal spot 5 in the lateral surface of the vessel there are two windows. Through one of them a LF converter 6 is inserted. On the other window a photomultiplier optical guide 10 is located. The vessel end opposite to the HF radiator is fit with a conical cover coated on the inside with sound-absorbing corrugated rubber. The hydrophone 8 is mounted through the vessel cap so that its detector of diameter 2 mm and thickness 0.25 mm is behind the focal spot of the radiator at a distance of 50 mm from it. The diameter of the radiating surface of the LF converter situated at a distance of 30 mm from the center of the focal spot of the HF radiator is 15 mm. The HF converter frequency is 19.9 kHz.

Preamplified output signals of the photomultiplier *L* and hydrophone *H* arrived at the storage oscilloscope 13 and were analyzed by computer 14. Examples of *L* and *H* recording are given in Fig. 1b.

The measurements made with the use of a calibrated hydrophone have shown that in the precavitation regime the sound pressure P in the focal spot of the radiator is related to the HF radiator voltage by the relation $P(10^5$ Pa) = kU/(V), and the radiated power throughout the investigated range of voltages is proportional to U^2 with an accuracy no lower than the measurement accuracy. Here k = 0.093 Pa/V.

The preparation for the experiment included the following operations. The vessel was filled with a liquid from an auxiliary reservoir through the discharge pipe in the laminar regime in order to prevent entrapment of gas bubbles in the process of filling. Then the liquid was allowed to settle in a cell for 48 h, after which it was subjected to degassing under the action of ultrasound for 15 min at a radiator voltage of 170 V (≈10 W/cm^2). The gas content thereby decreased by 20–25% compared to the equilibrium content [23, 26]. Preliminary degassing of the liquid considerably increases the reproducibility of results, since after such a treatment the gas content under the action of ultrasound remains practically unchanged in the course of the experiment. Upon the degassing, a cover was put down on the cell and the liquid was again allowed to settle for 15 h.

The HF generator made it possible to excite ultrasound vibrations in the cw and pulsed modes. The pulse width τ was varied over the 0.1–100-msec range and the pulse-repetition interval T was varied from 1 to 1000 msec. The ultrasound pulse shape is shown in Fig. 1c.

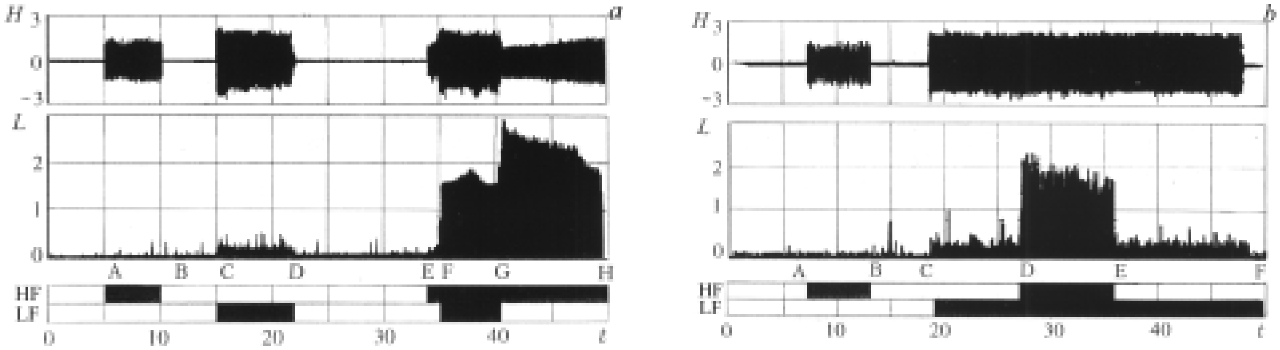

Fig. 2. Time oscillograms of output signals of the hydrophone H (upper oscillogram) and the photomultiplier L (lower oscillogram). The pulse duration τ of the HF field is 2 msec; the pulse repetition rate T is 300 msec; the radiator voltage is 135 V; the oscillation amplitude of the LF radiator is 8 μm: a, after the simultaneous operation (portion GH) the LF field is switched off; b, the HF field is switched off. H, L, V; t, sec.

Note that at a slow scan (Fig. 2) the low-intensity SL can be masked by background flashes. They are rather rare (less than ten flashes per second); therefore, at a scanning speed (Fig. 1b) they practically do not impede measurements.

Results of the Investigations. Figure 2a presents the results of the simultaneous recording of the hydrophone signal H (upper oscillogram) and the photomultiplier signal L (lower oscillogram). The time of operation of the HF and LF radiators is marked in the lower part of the figure by colored portions of the upper and lower bands under the figure. First the HF and LF radiators (portions AB and CD, respectively) were switched on separately, then the HF radiator (EF) again and both radiators simultaneously (FG), whereupon the LF radiator was switched off and the HF radiator continued to operate (GH).

Thus, the portion FG shows the SL intensity under the interaction of the two fields and the portion GH — the intensity generated by the HF field after the LF field was switched off. In this case, the modes of operation of the radiators were chosen so that the HF field intensity slightly exceeded the threshold I^*_{HF} at which SL arises and the LF field intensity was much higher than the threshold I^*_{LF}. Accordingly, with the separately operating HF radiator the averaged signal from the photomultiplier is ~17 mV and with the separately operating LF radiator — ~190 mV. It is seen from the figure that the result of the joint action of the two fields exceeds several times the sum of the results of their separate action. At the instant the LF radiator is switched off with the HF radiator on (at the end of the time interval FG) the SL intensity suddenly increases and then slowly decreases.

Figure 2b shows the results of an experiment similar to the first one with the same modes of operation of the radiators. In the time intervals AB and CD, the HF and LF radiators were switched on alternately, in the interval DE — both radiators simultaneously, and in EF — only the LF radiator. Thus, the difference from Fig. 2a lies in the sequence of switching off the fields after their simultaneous operation, namely; the HF radiator was switched off and the LF radiator continued to operate. As in the first case, at a concurrent operation of the radiators a considerable amplification of the SL was observed. However, two essential features compared to the previous experiment were revealed;

1) at the instant the high-frequency field was switched off there was no second jump of the SL intensity;

2) when the HF field was switched off the SL intensity dropped practically instantaneously to the initial value created by one LF field, i.e., the influence of the aftereffect of the switched-off (HF) field on the SL intensity generated by the operating (LF) field was absent.

Figure 3 presents the results of the SL recording in the course of the experiment performed according to a radically differing scheme, namely, first the LF field was switched off for a short time and then, some time Δt after termination of the LF radiation operation, the HF field was switched on. Thus, in this case, the actions of the LF and HF fields on the liquid are separated in time. The modes of operation of the LF and HF radiators were the same as in the experiments whose results are given in Fig. 2. It is seen that the memory of the stimulating action of the LF field on the activity of the HF-field-generated cavitation remains for a fairly long time. If Δt is small or equal to zero

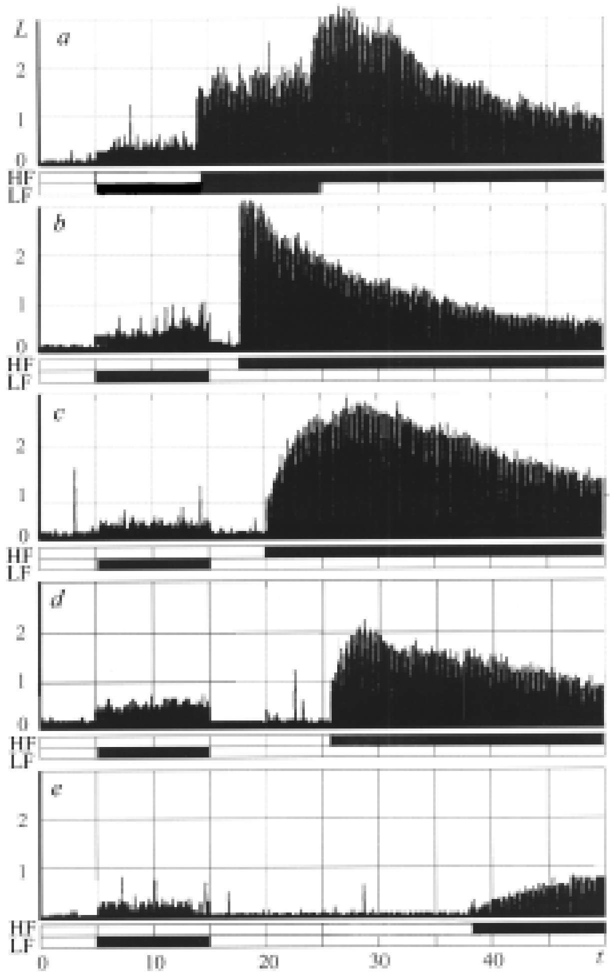

Fig. 3. Dependence of L on time t in the case where the LF and HF fields are switched on separately for different time intervals: a) Δt = 0 sec; b) 2.5; c) 0.5; d) 11; e) 23. The other parameters are the same as in Fig. 2. The running time of the HF and LF radiators is marked in the lower part of the figures by colored portions of the upper and lower bands, respectively. L, V; t, sec.

(<1–2 sec, see Fig. 3a, b), then at the instant the LF field is switched on the SL intensity abruptly increases to values close to the maxima attained under the conditions of the experiment presented in Fig. 2a. Upon the switch-on of the HF field at larger Δt (Fig. 3, c–e) L smoothly increases, reaches L_{max}, and then slowly decreases, tending to some limiting value. With increasing Δt the attained value of L_{max} decreases, as does the growth rate of L. This is obviously due to the relaxation during the time interval Δt of the changes in the cavitation properties of the liquid caused by the action of the LF field. In some cases, the time of complete relaxation, i.e., the time scale of the memory, reaches several hours. During this period the liquid returns to the initial state and the value of L upon the switch-on of the HF field is practically equal to that measured prior to the action of the LF field, i.e., of the order of 17 mV for the conditions of the given experiment.

Figure 4, I shows the time dependences of the SL generated under the action of the HF field with a short-term superposition of the LF field for various intensities of the HF field with the LF field intensity greatly exceeding the SL threshold I^{*}_{LF}. The moments of switching on and off of the LF field are indicated by arrows pointing upwards and downwards, respectively. Averaging was performed over three experiments.

If the HF field intensity is somewhat lower than or equal to the SL threshold, then under the action of the LF field L abruptly increases, reaches the limiting value, and then slightly changes with time. As soon as the LF field is switched off the SF intensity generated by the HF field decreases, tending to some limiting value, which is normally

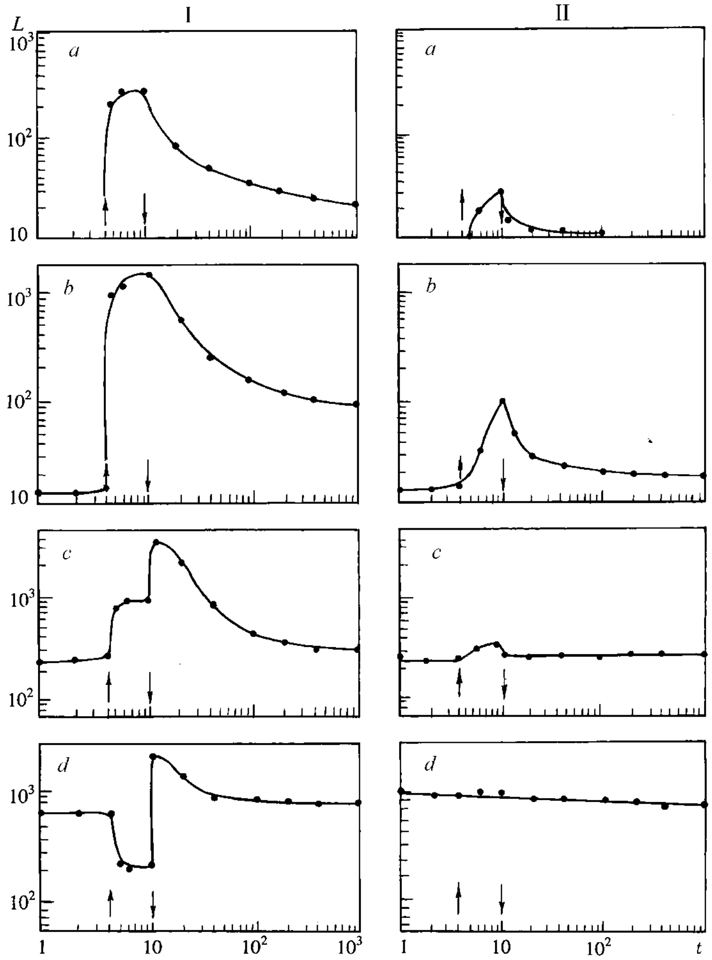

Fig. 4. Dependences of L on time t for various intensities of the HF field at an LF field intensity much higher than the cavitation threshold (A = 12 μm) — I — and at an LF field intensity of the order of the cavitation threshold (A = 1.5 μm) — II: a) U = 55 V; b) 75; c) 125; d) 150. The other parameters are the same as for the conditions of experiments whose results are given in the previous figures. Dots indicate measurement data. L, mV; t, sec.

much higher than that of the SL intensity separately generated by the HF field prior to the switch-on of the LF field. The value of L measured during the simultaneous operation of the two radiators considerably exceeds the sum of the L values measured when the radiators were switched on separately. If the HF field intensity is higher than the threshold I^*_{HF} (Fig. 4, I, b), then under the action of the LF field L suddenly reaches the threshold value and then slightly changes with time. At the instant the LF field is switched on a second jump of the SL intensity is observed and only then does its decrease begin. If the HF field intensity is much higher than the SF threshold ($I_{HF} >> I^*_{HF}$) (Fig. 4, I, d), then after the LF field is switched on the total intensity of the SL does not increase, but decreases. At the instant the LF field is switched off, a second jump of L is observed.

At a low intensity of the LF field (of the order of the cavitation threshold or lower, see Fig. 4, II, a–d) the character of the $L(t)$ dependences is approximately the same as in the previous case. However, there are also certain special features: when the LF field is switched on L increases not so much as in the previous case, and this increase is smooth, and not abrupt; when the LF field is switched off, the second jump of L is not observed whatever the HF field intensity. Moreover, the rate of decrease in L when the LF field is switched off (i.e., the relaxation rate of the cavitation properties of the liquid) is much higher compared to the relaxation rate after the action of an intense LF field (Fig. 2, 3). At a high intensity of the HF field (Fig. 4, II, d) the additional action of the LF field practically causes no increase in the SL intensity.

Discussion. As is seen from the above graphs, the result of the interaction of the two fields is strongly dependent on the mode of insonification. One can distinguish four modes of operation of the radiators (when they are switched on separately) such that in going from one to another the effect of SL amplification changes very significantly and, in some cases, not only quantitatively but also qualitatively: (I) the ultrasound intensity I is much lower than the intensity I^* corresponding to the threshold of the appearance of SL: $I << I^*$; (II) I has a value of the order of I^* and lies in the range of $0.5I^* < I < (1.5–2)\,I^*$; (III) I is not much higher than I^*, namely, $2I^* < I < 5I^*$; and (IV) $I > 10I^*$.

The maximum amplification of SL is observed if the HF radiator operates in mode II, i.e., if $0.5I^*_{\mathrm{HF}} < I_{\mathrm{HF}} < 2I^*_{\mathrm{HF}}$ and the LF radiator — in mode IV ($I^*_{\mathrm{LF}} >> I_{\mathrm{LF}}$) or in mode III ($2I^*_{\mathrm{LF}} < I_{\mathrm{LF}} < 5I^*_{\mathrm{LF}}$).

The mechanism of SL amplification associated with the direct interaction of the fields (see above items 1–3) are obviously realized only if both fields are on. The fact that for the majority of modes at the instant the LF field is switched off the decrease in the SL intensity is not instantaneous but smooth permits suggesting that the contribution of these mechanisms to the effect being investigated is small and the main factor is likely to be the generation of new cavitation nuclei upon the bubble collapse. These nuclei are not stabilized by the surface film; therefore, as soon as the LF field is switched off they rapidly reduce their sizes due to the gas diffusion from the bubble into the environment. As a result, the number of bubbles cavitating under the action of the HF field decreases, which leads to a decrease in the SL intensity. This hypothesis is verified by the fact that when the LF field is switched off the intensity of the acoustic signal received by the hydrophone (Fig. 2, upper oscillogram, portion GH) slowly increases. This means that the ultrasound absorption in the cavitation region decreases obviously due to the decrease in the bulk density of bubbles across the sonic wave.

From the point of view of this model the influence of the aftereffect of the LF field on the SL intensity generated by the HF field with alternate switch-on of the LF and HF fields (Fig. 3) is explained as follows. When the LF field is switched off the new cavitation nuclei live for some time, providing a higher SL generation efficiency in the HF field. As is seen from Fig. 3, if the interval Δt is small, then L increases stepwise when the HF field is switched on, and the values obtained thereby are approximately equal to $L_{\max}$ (Fig. 2). Thus, in the absence of direct interaction between the fields, too, the resulting amplification of the sonoluminescence is not smaller than in the case of the simultaneously operating radiators.

Practically, the instantaneous fall of L as soon as the HF field is switched off (with the LF field on, Fig. 2b) does not contradict the hypothesis about unstable nuclei either. Indeed, the bubbles cavitating under the action of the HF field are at least an order of magnitude (to be more precise, for the conditions of the experiments described above — about 40 times) smaller than the bubbles cavitating under the action of the LF field. Therefore, neither the HF bubbles nor, the more so, their fragments can serve as cavitation nuclei for the LF field, which explains the absence of the aftereffect of the HF field on the cavitation generated by the LF field.

Attention is drawn to the jump of the SL intensity observed as soon as the LF field is switched off if the HF radiator operates in mode I or II and the LF radiator — in mode III or IV (Fig. 2a, Fig. 4, I, c, d). To explain this feature, it is necessary to take into account that at a large concentration of cavitation bubbles, as a result of the strong interaction between them, the bubbles can lose their spherical form in the early stage of collapse and the rate of the latter can decrease. As a result, the conversion efficiency of the sound energy to the energy of shock waves and thermal energy decreases [31]. This can lead to a corresponding decrease in the intensity of the cavitation effects, including the SL. The screening effect of the cavitation region, too, can have a negative influence on the cavitation activity at a large concentration of bubbles [5]. At a fairly high intensity of the HF and LF fields the total density of the bubbles may turn out to be higher than the optimum density at which their influence on one another is still weak. When the LF field is switched off the number of bubbles in the cavitation region rapidly decreases and, possibly, at some instant, their density approaches the optimum density corresponding to the SL intensity maximum. Probably, this can cause an additional burst of L when the LF field is switched off.

The absence of the influence of fragments of HF bubbles on the LF-field-generated cavitation leads to the fact that such a burst is not observed with the HF field off and the LF field on (Fig. 2b).

The absence of an increase in L at the instant the LF field is switched off at a low intensity of the LF field (Fig. 4, II) is due to the fact that the additional action of the LF field in this regime practically does not increase (or slightly increase) the number of bubbles in the cavitation region generated by the HF field. Therefore, there is not any noticeable change in the concentration of bubbles in the case where the LF field is switched off either. And if the bubble concentration under the simultaneous action of the HF and LF fields was above optimum, it will remain in the state of oversaturation upon the switch-off of the LF field as well.

The effect of oversaturation of the cavitation region with bubbles is strongly pronounced if $I_{HF} >> I^*_{HF}$ and $I_{LF} > 10I^*_{LF}$. In this case, already under the action of only one HF field so many cavitation bubbles are generated that their density is close to the limiting one at which an increase in the number of bubbles leads to a decrease in L. Therefore, when the LF field generating additional bubbles is switched on the SL intensity decreases (Fig. 4, I, d). At the instant the LF field is switched off L suddenly increases to values exceeding the sum of the intensities generated separately by the LF and HF fields and then, as in the other cases, slowly decreases.

Thus, if the intensity of the LF field is much higher than the cavitation threshold, then the prevailing mechanism of SL amplification is the generation of new cavitation nuclei upon the collapse of cavitation bubbles excited by the LF field. Then these nuclei cavitate under the action of the HF field, increasing the integrated SL intensity.

If the LF field intensity is lower than the SL threshold, then the LF bubbles, i.e., the bubbles pulsating under the action of the LF field, practically do not collapse and do not generate additional cavitation nuclei. In this case, a marked amplification of the SL is only observed for HF field intensities of the order of the SL threshold, i.e., $0.5I^*_{HF} < I_{HF} < 1.3I^*_{HF}$, and the aftereffect of the LF field either is absent or is short-term. In this case, the SL amplification is likely to be determined by the mechanisms associated with the direct interaction of the fields, i.e., by their combining, the periodic decrease in the quasi-static (with respect to the HF field) LF field pressure, and the widening of the spectral composition of the resulting field.

CONCLUSIONS

1. It has been shown that the effect of nonadditive amplification of sonoluminescence is observed not only under the simultaneous action of the fields on the liquid, but also in the HF field after preliminary insonification of the liquid by the LF field. The effect of a long-duration aftereffect of the LF field on the cavitation generated by the HF field has been revealed.

2. It has been established that at LF field intensities exceeding the cavitation threshold the main mechanism of sonoluminescence amplification is the generation of cavitation nuclei by bubbles pulsating under the action of the LF field upon their collapse. Since the new nuclei contain much less air than the initial bubble steadily existing in the liquid, they collapse in the HF field at a higher rate, which can provide an increase in the energy conversion efficiency and concentration.

3. The observed decrease in the cavitation activity at HF and LF field intensities many times exceeding the threshold values at which sonoluminescence arises has been explained by the strengthening of the interaction between the bubbles when they oversaturate the cavitation region. As a result, the probability that the bubbles will lose their spherical form in the early stage of collapse increases and the collapse rate can decrease.

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NOTATION

A, oscillation amplitude of the radiator, μm; f, sound field frequency, kHz; H, output signal of the hydrophone, V; I, ultrasound intensity, W/cm^2; I^*, threshold intensity, i.e., minimum ultrasound intensity at which sonoluminescence arises, W/cm^2; L, output signal of the photomultiplier, V; P, sound pressure, Pa; P_0, hydroacoustic pressure, Pa; P_{LF}, acoustic pressure generated by the LF field, Pa; σ, surface tension, mN/m; R, bubble radius, m; τ, duration of ultrasound field pulses, msec; T, pulse repetition interval of the ultrasound field, msec; t, current time, sec; Δt, time interval upon the switch-off of the ultrasound field. Subscripts: LF, low-frequency; HF, high-frequency; max, maximum.

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