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**ARTICLE** *in* ULTRASONICS SONOCHEMISTRY · NOVEMBER 2003

Impact Factor: 4.32 · DOI: 10.1016/S1350-4177(03)00097-X



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Ultrasonics Sonochemistry 10 (2003) 337–341
Ultrasonics SONOCHEMISTRY
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# Study into mechanisms of the enhancement of multibubble sonoluminescence emission in interacting fields of different frequencies

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Received 29 October 2002; accepted 10 March 2003

**Abstract**

The main factor of the enhancement of sonoluminescence (SL) emission by the interaction of two fields of highly different frequencies is the generation of new cavitation nuclei upon collapse of bubbles driven by the low-frequency (LF) field. The factors connected with the direct interaction of the two fields play a significant role in the enhancement of SL emission only in the case when intensities of the fields are less or not much higher than the corresponding thresholds of SL emission. The phenomena of afteraction of the LF field on cavitation generated by the high-frequency field is explained also by the generation of new nuclei upon collapse of bubbles driven by the LF fields.


*PACS:* 78.60
*Keywords:* Sonoluminescence; Fields interaction; Cavitation

## 1. Introduction

It has been shown in [1–4] that the action of a low-frequency (LF) field on the cavitation zone generated by a high-frequency (HF) field is an efficient method for increasing the multibubble sonoluminescence (SL) emission. In the interacting HF and LF fields there was observed an enhancement of SL more than additive. In a combined field generated by the simultaneously operating pulsed HF and LF radiators the SL intensity exceeds in some cases many times the sum of the SL intensities initiated in operation of each of the radiators individually. Results of investigation of ultrasonic capillary effect [5], chemical activity of cavitation [6–10], erosion rate and drug delivery to suspended cells [11–13] in two-frequency fields are in agreement with [1–4]. Recently HF pulses were used for boosting sonoluminescence generated by single bubble oscillating in LF field [14].

The possible mechanisms of multibubble SL enhancement in the interacting fields are as follows [1–5]:

### 1.1. Broadening of the spectral composition of the resultant field

The cavitating liquid is a substantially nonlinear medium. In interaction of the fields with frequencies $f_1$ and $f_2$, in such a medium the waves of combined frequencies $f_1 + f_2$ and $f_1 - f_2$ can be generated [15]. The same is valid for the harmonics of the two fields. Therefore, the resultant field covers a set of the frequencies substantially wider than the sum of the spectra of the fields. This must lead to the broadening of the range of the size of bubbles involved in the cavitation process and, consequently, to an increase in the total number of cavitating bubbles.

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doi:10.1016/S1350-4177(03)00097-X

*1.2. Periodic decrease in the total quasistatic pressure in the LF field*

If the frequency of the LF field is substantially (10 times or more) lower than that of the HF field, than the LF field is quasistatic in relation to the HF field. Within the half-period of LF-field rarefaction the total pressure $P = P_0 + P_{LF}$ (where $P_0$ is the hydrostatic pressure, $P_{LF}$ is the negative pressure initiated by the LF field) decreases. As a result, nuclei increase their size, the cavitation threshold decreases, and the number of cavitation bubbles increases. In the half-period of LF-field compression ($P_{LF} > 0$), the total quasistatic pressure increases which may lead to the quicker collapse of the bubbles formed during the half-period of rarefaction of the LF-field. As a consequence, the pressures and the temperatures attained in the bubbles will also increase that can be a reason for the increase in the SL intensity [3]. In the compression half-period of the LF-field quasistatic pressure is increased. In accordance with [16–18] this may cause an increase of the efficiency of the HF bubbles collapse.

*1.3. Suppression of forming the stable clusters of cavitation bubbles*

The bubbles in clusters are held near each other [19–21] and therefore interact strongly by shock waves and Bjerkness forces. As a result of these interactions, the bubbles can undergo deformations. Since the spherical shape of a bubble is unstable under collapse any deformation is built up rapidly and a bubble loses its spherical form already in the early stage of collapse. The nonspherical collapse is characterized by the substantially less efficiency of converting and concentration of the energy as compared with the collapse of spherical bubbles [22]. Therefore, the formation of cavitation clusters can be considered to be one of the reasons for the decrease in the intensity of multibubble sonoluminescence with increase of the bubble concentration in the cavitation zone. Apparently, the shock waves and the liquid microjets generated by the collapse of large LF bubbles hinder the formation of HF bubble clusters by seeding the cavitation nuclei throughout the liquid volume. As a result, the mean efficiency of the energy converting by cavitation bubbles may increase.

*1.4. Generation of a great amount of new nuclei by LF bubbles*

By collapse the cavitation bubbles break down into fragments. The number of these fragments, i.e. smaller bubbles, can attain 40 [16]. Since their sizes are substantially smaller than the size of the initial bubble, these nuclei can be suitable for cavitation in the HF field. These new nuclei contain much less air than the initial bubbles from which these nuclei have been formed; therefore, they are likely to collapse in the HF field at a higher rate than the bubbles drown from the nuclei stably existing in the liquid. Thus, owing to this mechanism both the number of cavitation bubbles and the efficiency of their collapse can increase. The last can entail an increase in the maximum pressures and temperatures attained in the vapor–gas mixture inside bubbles and, as a consequence, an increase of the SL intensity.

The results provided in the present work make it possible to evaluate the contribution of the indicated mechanisms to the effect of SL enhancement by the interaction of the ultrasonic fields highly differing in frequency.

## 2. Experimental

Fig. 1 shows schematic diagram of the experimental set-up. Experimental procedure is described in detail in [1]. Figs. 2 and 3 show results of recording simultaneously the output signal H of a hydrophone (the upper oscillogram) and of the photomultiplier output $L$ (the lower oscillogram). Hard lines in the top of the figures show working intervals of the transducers. The lower line refers to the LF (27.2 kHz) transducer, the upper line refers to the HF (880 kHz) transducer.

Fig. 2 shows the time dependencies of $H$ and $L$ generated by the HF field alone, than after short silence interval—by the LF alone, during joint action of both transducers, and by HF alone after switching off LF transducer.

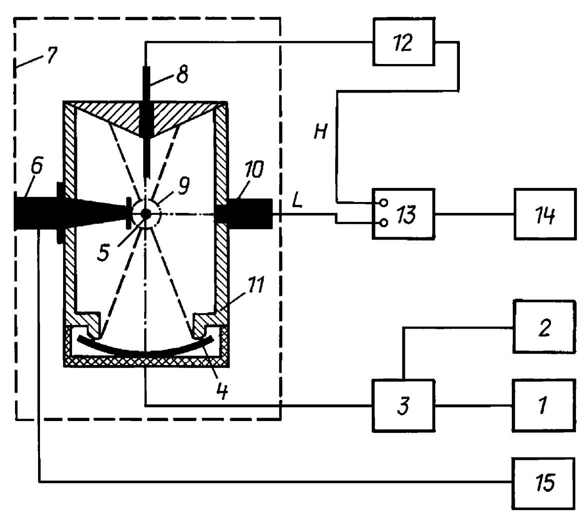


Fig. 1. Experimental arrangement: (1) HF generator, (2) pulse generator, (3) mixer, (4) HF transducer, (5) focal spot of the HF transducer, (6) LF transducer, (7) light-tight box, (8) hydrophone with bandwidth from 10 kHz to 5 MHz, (9) intensive cavitation zone, (10) photomultiplier with bandwidth from 200 to 700 nm, (11) preamplifier, (12) spectrum analyzer, (13) oscilloscope, (14) PC, (15) LF generator.

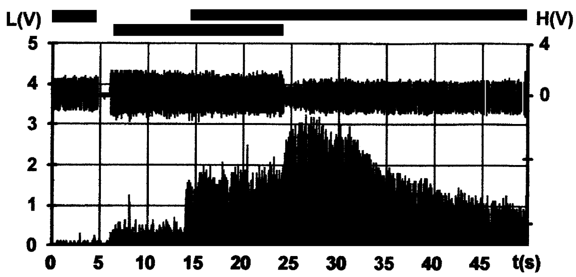


Fig. 2. Time history of the hydrophone output $H$ (upper record) and of the photomultiplier $L$ (lower record). HF field parameters: pulse period—100 ms, pulse duration—2 ms, driving voltage $U_{HF} = 55$ V; LF field parameters: $U_{LF} = 750$ V, vibration amplitude $A$ of the radiating tip is 12 μm. (Threshold voltage for SL generation by HF field $U_{HF,th} = 50$ V, threshold amplitude for SL by LF field $A_{LF,th} = 1$ μm.) $I_{HF} > I_{HF,th}$, $I_{LF} \gg I_{LF,th}$.

Fig. 3 shows the results of an experiment according to a different procedure: first, the LF field was switched on for a short time, then after certain silence interval $\Delta t$ 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 regimes of operation of the LF and HF radiators were maintained the same as in the experiments whose results are shown in Fig. 2.

If $\Delta t$ is small ($\approx$1–2 s, Fig. 3a), then at the moment of switching on the HF field the SL intensity abruptly increases up to the values close to the maximum intensity attained under the experimental conditions given in Fig. 2 during simultaneous operation of both transducers. At large rest time $\Delta t$ (Fig. 3b, c) after switching on the HF field the SL intensity smoothly increases, attains its maximum $L_{max}$ and afterwards slowly decreases tending to some limiting value. As $\Delta t$ increases, the attained $L_{max}$ value decreases along with the rate of growing $L$. This proceeds apparently as a consequence of the relaxation for time $\Delta t$ of the changes in the cavitation properties of a liquid due to the action of the LF field.

The data in Fig. 4 are obtained at the intensity of the stimulating LF field being much higher than its threshold intensity for SL appearance $I_{LF,th}$, and in Fig. 5 at the LF field intensity of about $I_{LF,th}$. If the intensity of the HF field is equal to or slightly smaller than the SL threshold (for HF when operating alone) and the intensity of the LF fields exceeds much $I_{LF,th}$ (Fig. 4a), then on switching on the LF field, the SL intensity $L$ abruptly increases, attains the limiting value and then slightly changes with time. After switching the LF field off, the intensity of sonoluminescence generated by the HF field decreases smoothly. In this case the SL intensity generated by two fields exceeds the sum of the SL intensities generated when they are switched on separately. If the HF field exceeds slightly the threshold intensity $I_{HF,th}$ (Fig. 4b, c), then due to the action of the LF field the SL intensity quickly attains its limiting value and then changes only by small quantity with time. At the moment of switching the LF field off, the second jump in the SL intensity is observed (as in Fig. 2) and only afterwards its decrease starts. If the intensity of the HF field exceeds much the SL threshold $I_{HF} \gg I_{HF,th}$ (Fig. 4d), then on switching the LF field on the total SL intensity does not increase, on the contrary, it decreases. At the moment of switching the LF field off, the second jump in the SL intensity is observed. Here, the maximum SL intensity substantially exceeds the intensity of sonoluminescence generated by the HF field before the stimulating action of the LF field.

If the intensity of the LF field is not much higher than $I_{LF,th}$ (Fig. 5) attained enhancement of SL intensity is

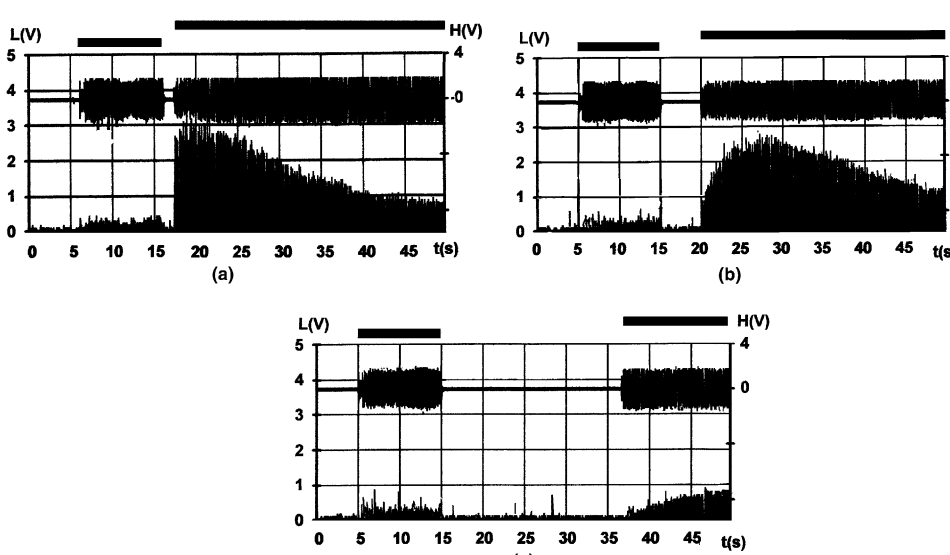


Fig. 3. Time history of the hydrophone output $H$ (upper record) and of the photomultiplier $L$ (lower record) for different time intervals $\Delta t$ between LF field off and HF field on: $\Delta t \approx 2$ s (a), 5 s (b) and 22.5 s (c). Other parameters are the same as in Fig. 2.

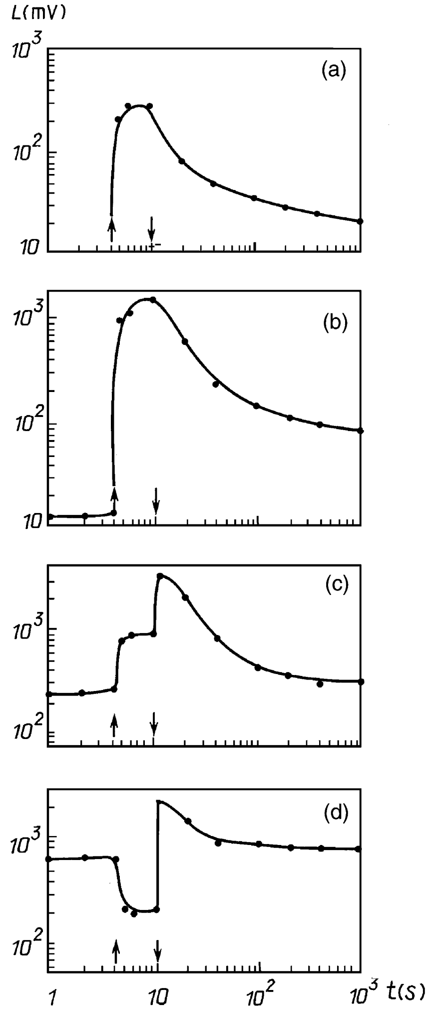


Fig. 4. $L$ versus $t$ for different HF field intensities, LF field intensity is much higher than LF field SL threshold ($A_{LF} = 12A_{LF,th}$): $I_{HF} \leqslant I_{HF,th}$ (a); $I_{HF} \geqslant I_{HF,th}$ (b); $I_{HF} > I_{HF,th}$ (c); $I_{HF} \gg I_{HF,th}$ (d); $I_{LF} \gg I_{LF,th}$. Other LF and HF field parameters are the same as in Fig. 2.

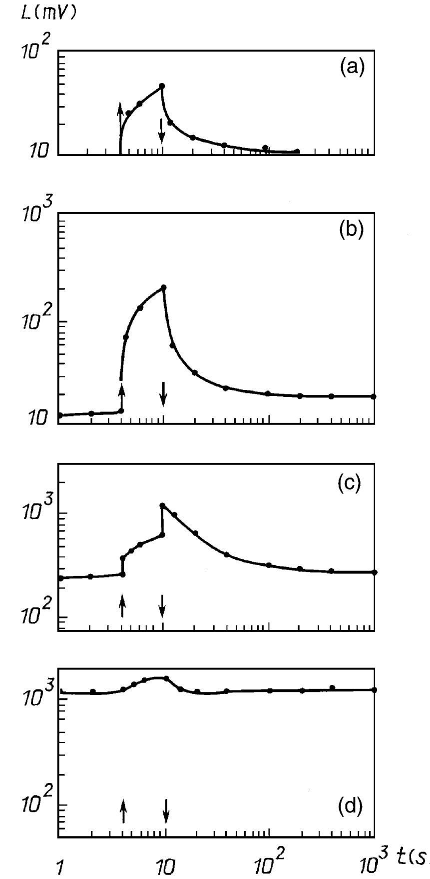


Fig. 5. $L$ versus $t$ for different HF field intensities, LF field intensity is not much higher than LF field SL threshold ($A_{LF} = 2A_{LF,th}$): $I_{HF} \leqslant I_{HF,th}$ (a); $I_{HF} \geqslant I_{HF,th}$ (b); $I_{HF} > I_{HF,th}$ (c); $I_{HF} \gg I_{HF,th}$ (d); $I_{LF} \gg I_{LF,th}$. Other LF and HF field parameters are the same as in Fig. 2.

much smaller than in previous case, aftereffect is less pronounced.

## 3. Discussion of the results

As can be seen from the plots presented above, the result of interaction of two fields strongly depends on the intensities of both fields.

The above mechanisms (1.1, 1.2, 1.3) of SL enhancement related to the directinteraction of the fields are implemented only if both fields are switched on. The fact that for the majority of regimes at the moment of switching the LF field off the SL intensity does not momentarily fall down but, on the contrary, it increases in some cases and than decreases smoothly, or just decreases smoothly, allows us to consider that the contribution of these mechanisms to the investigated effect is small and the main factor is the generation of new cavitation nuclei by the collapse of the bubbles. After switching the LF field off, these nuclei decrease their sizes due to diffusion of the gas from a bubble in the surrounding liquid and gradually completely dissolve. Therefore, the amount of bubbles cavitating under the HF-field action decreases, thus leading to a decrease in the SL intensity. This hypothesis is confirmed by the fact that after switching the LF field off, the intensity of the acoustic signal received by the hydrophone (Fig. 2) decreases suddenly and then slowly increases. This indicates that the ultrasound attenuation in the cavitation region decreases as a consequence of the decrease in the volume density of bubbles on the path of the acoustic wave. In the context of this model it is also easy to explain the aftereffect of the LF field on the intensity of sonoluminescence generated by the HF field in the case of separate switching-on of the LF and HF fields (Fig. 3). After switching the LF field off, new nuclei live for a sufficiently long time thus providing a higher SL intensity in the HF field.

The jump in the SL intensity observed on switching the LF field off for the case when both fields operate at the intensity that substantially exceeds their cavitation threshold can be attributed to the following reason: at the large concentration of cavitation bubbles due to strong interactions between them, the rate of their collapse can decrease and the bubbles can lose their spherical form in the early stage of collapse. As a result, the efficiency of conversion of the acoustic energy to the energy of shock waves and the thermal energy decreases, when bubbles density in cavitation field is higher than the optimal one. This can entail the corresponding decrease in the intensity of the cavitation effects including sonoluminescence. But at the moment of switching the LF field off, the number of bubbles in the cavitation region rapidly decreases and it is possible that at some moment their density approaches the optimum one that corresponds to the maximum SL intensity.

Thus, if the LF field intensity is substantially higher than the cavitation threshold, the prevailing mechanism of SL enhancement is the generation of new cavitation nuclei on collapse of the cavitation bubbles initiated by the LF field. Under the action of the HF field these nuclei then cavitate thus increasing the integral intensity of sonoluminescence.

If the intensity of the LF field is lower than the SL threshold, then the LF bubbles, i.e. the bubbles pulsating under the LF-field action do not virtually collapse and do not generate additional cavitation nuclei.

In this case, the pronounced SL enhancement is observed only for the HF-field intensities of about a SL threshold, i.e. $0.5I_{\mathrm{HF,th}} < I_{\mathrm{HF}} < 1.3_{\mathrm{HF,th}}$ and the LF-field aftereffect is either absent or of small level. In these insonation regimes the enhancement of sonoluminescence is apparently determined by the mechanisms described in items 1.1–1.3, i.e. by direct interactions of the fields.

## 4. Conclusions

The main factor of the enhancement of SL emission in interacting fields of highly different frequencies is the generation of new cavitation nuclei upon collapse of bubbles driven by the LF field. On collapse the cavitation bubbles break down into fragments. Since sizes of these fragments are substantially smaller than the size of the initial bubble, these nuclei can be suitable for cavitation in the HF field.

The factors connected with the direct interaction of the fields such as interference of the fields or generation of waves with combined frequencies may play significant role in enhancement of SL emission only in the case when intensities of the fields are less or not much higher than the thresholds of SL emission.

## Acknowledgements

The research has been supported by the European INCO-Copernicus Program and by Belarusian Foundation for Basic Research. N.V. Dezhkunov is thankful to the Consorzio per l'Incremento degli Studi e delle Ricerche degli Istituti di Fisica di Trieste for the support of his visit to the Laboratory of Liquid Structure and Cavitation of the University of Trieste. Authors are thankful to Prof. G. Iernetti for his assistance in preparation of the manuscript.

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