Physical mechanisms analysis of ultrasonic high amplitude cleaning

V Prikhodko¹, M Karelina¹, D Fatyukhin¹ and V Moiseev²

¹Moscow Automobile and Road Construction State Technical University (MADI), 64 Leningradsky Prospect, Moscow, 125319, Russia
²Belgorod State Technological University named after V.G. Shukhov, 46, Kostukova str., Belgorod, 308012, Russia

¹E-mail: din_prof@mail.ru

Abstract. The article discusses physical factors that have the greatest impact on the high-amplitude ultrasonic cleaning process course. It has been revealed that an increase in oscillations amplitude a piston ultrasonic transducer over 10 ... 12 μm leads to qualitatively new effects formation, which make it possible to expand ultrasonic cleaning technological capabilities. Usually, dynamic effects organization during ultrasonic cleaning is associated with cavitation bubbles action capable collapsing with local shock waves formation, pressure of which reaches 1000 atmospheres, narrow cumulative liquid streams directed toward the solid surface, and new fragmentation bubbles-germ. In high-amplitude regimes, various scale hydrodynamic flows play a decisive role for cavitation effects distribution functions formation in working capacity and for occurrence in it of spatial self-organization certain manifestations. Different-scale acoustic flows effect influence on ultrasonic treatment zone erosion activity has been analyzed. Studies have revealed technological zones presence specific for this type of treatment. Ultrasonic cleaning features with direct collapsing cavitation bubbles use are given in the articles. Possibility for expanding active cavitation erosion zone with high-amplitude ultrasonic cleaning is considered. Research conducting allowed to create effective specific technologies and several technological devices, as well as introduce them at leading industrial enterprises.

1. Introduction
During the mechanisms investigating and technological parameters of ultrasonic cleaning in the piston emitters fields at frequencies of 20 ... 25 kHz, the products cleaning efficiency located more than 10 mm from the radiating surface increases with an increase only about 3 microns in oscillation amplitude. Further amplitude increasing leads to an increase in the number of cavitation bubbles, bubble clouds formation which limiting the increase in technology efficiency [1, 2].

With amplitude oscillations increasing to large values (30 ... 50 μm), a bubble cloud consistent “compaction” is observed, but technological consequences of this process were not so unambiguous. Until the amplitudes of 10 ... 12 μm, the negative forecast was generally confirmed - cavitation erosion efficiency in weight terms grew very slowly; starting from 12 ... 15 μm, cavitation erosion growth — of course, where cavitation takes place — again became regular and significant enough to create new technically sound processing modes on its basis. Furthermore, for large oscillations amplitudes of the radiating surface at distances of 30 ... 70 mm from it, i.e. far beyond the active cavitation erosion zone,
sustained effects of cleaning products from some contaminants types (soluble lubricants, polishing paste residues, etc.) were observed without the slightest trace of cavitation damage [3, 4].

Thus, already at the first stage two fundamental technical results were obtained:

- proved the possibility of a significant increase in erosive ultrasonic cleaning performance for solid surfaces “heavy” contamination located in intense cavitation zone (up to 15 ... 20 mm from the transducer surface);
- rather extensive zone which remote from the transducer, was discovered in which certain types of ultrasonic cleaning were successfully carried out without any cavitation erosion manifestations.

Conducted large-scale studies in the high-amplitude ultrasound study revealed technological zones presence which characteristic for this type of processing (Figure 1).

![Figure 1. Technological zones schematic representation](image)

2. Large-scale acoustic flows

According to accepted classification, these hydrodynamic phenomena group includes flows, the characteristic closed circuit geometric size which is determined by the working capacity geometry with the containing medium and at least several times greater than the wavelength of sound in it.

The hydrodynamic flow arising on transducer surface serves as the primary means for transporting cavitation germ and bubbles from radiating surface towards the working zone. In high-amplitude modes, flows play a decisive role in the cavitation effects distribution functions formation in the working capacity and in occurrence in it certain manifestations of spatial self-organization. Speed of this flow reaches several meters per second, and, due to the Bernoulli effect, it is compressed in the transverse direction. This additionally increases the bubble cloud density, localizes the maximum cavitation activity in the closest zone to transducer and imparts special acoustic properties to this zone, which can be characterized as an increase in compliance, decrease in density and, accordingly, decrease in the effective acoustic wave medium resistance. Below, we consider the possibility that the bubbles which have passed into the far zone stop to collapse while retaining the ability to remove some contaminants due to other types of motor activity.
3. Acoustic microflows in fluid

First of all, experimentally established cleaning effect with high-amplitude radiation in the area where there are no cavitation collapses manifestations cannot be explained by anything other than the small diameter microflows effect and, accordingly, large curvature. Microflows are associated with oscillating (pulsating and wobbling) bubbles and receive from them elastic energy sufficient to remove contamination [5, 6]. Visual observations using high-speed imaging allowed us to observe the Eckart stream with many bubbles, with which, apparently, microturbulence associated with them is transferred.

In general, ultrasonic cleaning microflow mechanism of surface contaminants exists and effectively works in various technological situations. For example, at megahertz order frequencies, collapses almost do not occur due to energy smallness stored by the bubbles (the added mass is small). However, at these frequencies products industrial cleaning such as elements of solid-state electronics, printed circuit boards and other precision objects, which are strongly contraindicated for the dynamic erosion effect, is carried out.

Apparently, the main directly acting factor in microflow cleaning is the normal velocity component of the liquid in microturbulence for surface being cleaned, more precisely, the velocity gradient creating a normal surface force. Hence, in fact, it follows that the microflows are the most effective in this situation, i.e. large curvature flows. Microflow cleaning is especially effective on rough surfaces, in particular, contamination surfaces, with especially inhomogeneous ultrasound radiation front, etc. Microflow or weakly erosive ultrasonic effect also turns out to be optimal for such important pre-treatment as ultrasonic soaking of heavily soiled products.

It should be noted that the high cleaning efficiency of small-diameter turbulences is known in the engineering. For example, washing machines are produced in which vortex activator action is supplemented by bubbling through a tank with a small compressor into many small air bubbles which split the main large-scale turbulence into eddies of small diameter. Despite a sharp (2 ... 5 times compared with the same class and purpose machines) reduction in the main hydrodynamic activator power, such machines quite efficiently and effectively cope with the full programs set corresponding to their washing class and clothing cold laundry.

4. Ultrasonic cleaning features with collapsing cavitation bubbles direct use

Consider the solid surface cleaning problem from contamination in the general setting. The processing objectives are forced surface and contamination mechanical separation, as well as surrounding environment mixing to reduce the restoration likelihood for destroyed bond of the separated contamination with the surface. Note that here we are talking about removing pollution in a mechanical sense, although in principle, a variety of physico-chemical, chemical, thermal and other effects can be used or have a certain effect [7, 8].

For heterogeneous system coupled components mechanical rupture, they must be influenced either by dynamic forces associated with significant accelerations or due to large mass transfer velocity gradients in the host fluid boundary layer. Under any of these effects, different (in magnitude and / or direction) reactions occur in different components, and the difference forces with greater or lesser success tend to overcome the component bonds strength between themselves, break these bonds, and separate pollution from the surface.

Traditionally, everything related to the dynamic effects organization during ultrasonic cleaning is usually associated with the action of cavitation bubbles certain part capable of growing to a resonant size under suitable conditions and collapsing, i.e. implode with the local shock waves formation, the pressure in which reaches 1000 atmospheres, narrow cumulative liquid streams directed toward the solid surface, and new fragmentation bubbles-germ. The latter can, once again growing to a resonant size after some time, repeat collapse processes again and again.

It is known that any bubbles, including cavitation ones, always tend to be localized at the natural interface: it replaces a part of their surface, thereby reducing the surface tension energy. Therefore, the cavitation bubbles majority collapse and release accumulated elastic energy exactly where it is necessary from the main task of cleaning point of view - on the solid surface and pollution. Bubbles and, of course,
their fragmentation bubbles-germ are especially firmly fixed on all sorts of relief features - the mouths of cracks, pores, edges, roughness, etc. Since, as is known from the general solids theory, their erosion destruction has accumulative character or, as they say, cumulative character, this contributes to the effective solid and rough dirt destruction, and sometimes the surface itself being cleaned by ultrasound [9, 10]. However, not too hard contaminants - for example, fatty - as you know, can be removed from solid surfaces by slamming bubbles due to spraying them with shock waves and cumulative washing liquid jets (so-called emulsification cleaning).

Summarizing what has been said about the ultrasonic cleaning features with collapsing cavitation bubbles direct use, it can be concluded that in all these modes and zones we are dealing with the dynamic destruction nature and pollution separation, i.e. cleaning up.

5. Prerequisites for active cavitation zone expansion
Bubble in acoustic field pulses and oscillates at acoustic disturbance frequency. Bubble oscillations, like any material particle, with sufficiently large Reynolds numbers, i.e. high speeds, create a complex flows system around it, incl. circular. Therefore, in the zone closest to radiating surface with a high concentration of bubbles, where the medium wave impedance drops sharply, and pulsations amplitude increases for a given sound pressure amplitude, formation of bubble-turbulence assembly is quite natural, and at equal circular frequencies such an assembly is a stable pair of coupled oscillatory circuits.

However, such pairs transfer from radiating surface to the non-erosion-free zone looks unlikely - with a continuous decrease in acoustic pumping amplitude. Microflow carried by laminar flow at a speed of about 1 m / s would have to perform about a thousand revolutions in a 50 mm path and, of course, quickly decay over by centrifugal liquid spreading.

But in the same bubble cloud located at radiating surface, there are optimal conditions for bubble-turbulent pairs convergence with each other and their coalescence, i.e. formation of paired and even more complex ensembles, in which microflows, formed by separate oscillating bubbles, as if intercepted by each other, sharply reducing losses due to centrifugal scattering of liquid.

Thus, from a dense bubble cloud a large-scale flow makes completely different dynamic formations:
- bubbles that were at removal moment in the minimum values oscillation velocity phase and are capable, pulsating, to grow, reach a resonant size and collapse, creating shock waves and cumulative jets;
- single bubble-turbulent ensembles, rapidly decaying due to centrifugal liquid spreading and thereby opposing to hydrodynamic flow compression under the Bjerkness forces action and the Bernoulli effect;
- finally, coalesced multibubble ensembles with generalized curvilinear microflows that do not float, as would occur if they coagulate, have a large sail effect and are easily transferred by large-scale hydrodynamic flow over considerable distances.

Feature of such multi-bubble ensembles, which we call dynamic clusters, is ability to store significant reactive elastic energy in highly bent hydrodynamic microflows, which can be released and spent on performing mechanical work in collisions with phase boundaries or other heterogeneous systems and, accordingly, straightening the flow structure.

Obviously, such clusters also perform a useful work fraction on cleaning the products surfaces and in the erosion zone, but their contribution here is hardly noticeable against the cavitation erosion work background. In the far-field zone, they constitute the effect essence of non-erosive cleaning - practically interesting phenomena, but, as already noted, it seems too expensive due to large energy losses in cavitation cloud and in developed high-amplitude cavitation zone.

However, in the clusters presence with considerable elastic energy stored in them, it is possible by relatively small additional dynamic effect to force this energy to be released in a more efficient form for ultrasonic technology, for example, in the form of the same cavitation collapses as in main transducer developed cavitation zone. If in the existence zone for such bubble-turbulent dynamic clusters increase, in addition to existing acoustic field, sound pressure amplitude, for example, with an additional transducer, then bubble can again acquire the ability to collapse, destroying the existing hydrodynamic structure and, therefore, releasing the mechanical energy accumulated in it.
Direct experiment showed that high erosion activity is observed in cavitation bubbles large-scale flow non-erosional part in the area where the maximum bottom echo signal is applied to it, if the radiation and flow are directed normally to the bath bottom with cavitating water. Here, the bottom echo acts as an extraneous sound source relative to the main transducer. Other effective schemes for using reflected acoustic signals may be proposed, extending the active cavitation erosion zone.

From the technological application point of view, erosion activation variants of bubble clusters that do not collapse under normal conditions with additional, but not high-amplitude, ultrasonic transducers are of the greatest interest.

6. Conclusion
It can be argued that the experimental studies results confirm the assumptions made at initial analyzing the phenomena stage that occur with the powerful ultrasound piston radiation in a cavitating liquid medium. First of all, there was a direct confirmation of assumption that there is fundamental possibility, storing mechanical energy in the bubble-turbulent clusters form near the radiating surface, to store some of this energy in cavitation bubbles hydrodynamic flow at fairly large distances, in order to then acoustically activate these formations and to achieve the stored energy release in cavitation collapses form in the far radiation zone.

It was possible to show that not only specially organized reradiation of the main powerful ultrasound source, as in the bottom echo case, can be used to activate clusters transported in a large-scale hydrodynamic flow, but also other, additional ultrasound emitters, moreover frequency and phase of their radiation did not play any noticeable role.

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