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Average radiation force at high intensity: Measured data

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Measurements were done with HIFU transducer (3.1 and 4.3 MHz) in water tank at room conditions. Average radiation force (ARF) was measured by special ARF meter in pulse mode. The ARF meter was moved along the acoustic axis of the transducer from 0.7 F to 1.4 F, where F is the focal distance of the transmitter. The meter had diameter 0.5 inch and full reflection at normal incidence. Dynamic pressure amplitude at the focal spot was 4 MPa and 10 MPa. Experiment demonstrated: the ARF is growing function (~ 20%) at increasing of a passed distance. The ARF is not zero when the passed distance is not close to zero. Hence, the ARF contains contributions from 2 different models of the ARF: one is based on linear momentum of acoustic wave flow and another one – on nonlinear properties of acoustic media.

1. INTRODUCTION

Any acoustic wave flow can be described by dynamic radiation pressure – it is well known. If such wave flow interacts with some obstacle – we can see appearance of interesting phenomenon: steady radiation force. Average radiation force (ARF) is other name of this phenomenon. It needs to add, that term “average radiation force” means averaging for one period of oscillations (and it must be done in each period of oscillation). ARF measurements are done, usually, with weight balance devices – mechanical or electronic. That is why the ARF was earlier called “radiation force balance” – in old publications. It was applied in continuous wave mode only (and it continues now).

Many authors noted that the ARF is a subtle phenomenon in acoustics. It was true several decades ago. But in beginning of 1990 years we started applications of high intensity ultrasound and the ARF have stepped out of a frame “subtle phenomenon”. Now the ARF can be up to the atmospheric pressure in water-type liquids (100 kPa) and even slightly higher.

High intensity ultrasonic flow can be obtained with high intensity focusing ultrasonic (HIFU) transducers. Very frequently HIFU transducers are operated in pulse mode only – due to necessity of cooling between pulses. Existing meters of the ARF – like devices from Ohmic Instruments – have electronic weight balance meters with minimal time of measurements ~ 3 seconds. Hence, existing meters of the ARF are able to measure at averaging for several second. Hence, it would be better to get measured data with averaging inside radiated pulses only. Such special ARF meter – on a base of hydrophone – has been built and used in this project.

One of basic properties of the ARF: the ARF is a quadratic function of dynamic radiation pressure. Hence, the ARF is proportional to the power flux in acoustic wave flow. Such property of the ARF may generate opinion that the ARP is pure nonlinear phenomenon and it is consequence of the nonlinear properties of acoustic media. There were many such publications – review of these publications is not goal of this work. Formulated descriptions of the ARF models (as consequence of the nonlinear properties of acoustic media) have been presented, for example, in recent books [1, 2].

There are several versions of nonlinear model to explain the ARP. Books [1, 2] describe two versions, based on nonlinear properties of real acoustic media. First version is based on adiabatic dependence of pressure p on density ρ at very fast changes of density (it means: there are no any heat transfer between areas with positive and negative pressures in acoustic wave).

$$p = p_0(^{\rho}/_{\rho_0})^{\gamma} \qquad (1)$$

Where: p_0 and ρ_0 are ambient pressure and density in acoustic medium without waves, and γ is some parameter of this medium ($\gamma > 1$). This version of the ARF model can be applied for gases: adiabatic curves can be measured there directly and one can find parameter γ for such acoustic media in multiple publications. But measurement of γ for liquid media is very not easy action. Hence, it was needed another version for the nonlinear ARF model. Such second version is based on the first two coefficients (A and B) in Taylor series for function: expansion of acoustic medium at fast deformations.

$$p = A\left(\frac{\Delta\rho}{\rho_0}\right) + \frac{B}{2!}\left(\frac{\Delta\rho}{\rho_0}\right)^2 + \ \dots \qquad (2)$$

Actually, it is needed a ratio of the first two coefficients: B/A. Detailed description of experimental measurements and tables with experimental data for many liquids are in the book [1], p. 25 - 37.
So, we came to well known versions of nonlinear model for the ARF. There are expressions of the ARF for both versions of this nonlinear model and in the Eulerian and Lagrangian coordinate systems – in above noted books [1, 2].

But these expressions can generate some doubts among readers with background in nonlinear acoustics. One can find interesting plots in the book [2], Fig. 3-6 (p. 113). These experimental data demonstrate: if acoustic wave flow goes through nonlinear medium, distortions in acoustic waves grow with passed distance. Fig. 3-6 demonstrates dependence of harmonics (# 1, # 2, and # 3) on passed distance at dynamic pressure amplitude ~ 300 kPa. First harmonic decreases with the distance. But the harmonics # 2 and # 3 grow. It means: nonlinear distortions of acoustic waves in nonlinear medium is not some constant. Such distortions depend on the length of passes distance from the transducer to the observation point. Unfortunately, Fig. 3-6 does not contain any information about DC component (it is harmonic # 0). Such DC component is, actually, the ARF of the acoustic wave flow (more accurately: the ARF is proportional to the DC component). There is strong suspicion: 0-component is not some constant (or 0) for waves in the nonlinear medium. More ever, the DC component may depend on the passed distance as well – it follows from the technique of solution for nonlinear acoustic equations. Maybe, the ARF grows with the passed distance (in the media with low attenuation)? Such suspicion generated main goal of this work: experimental measurements of the ARF as function of passed distance in the nonlinear medium (water) and at high dynamic pressure amplitude: 4 – 10 MPa. Corresponding measurements have been done (in pulse mode). Measured results are presented and discussed below, in the sections 3 and 4.

It needs to say about one more possible model of the ARF, based on the changes of the linear momentum of the wave flow at interaction with some obstacle(s). Such model was developed in theoretical physics for any type of waves – see, for example, [3], p. 997 – 998. It is well known, that any wave flow transmits some energy that can be defined by its power flux (I) – it is quantity of transmitted energy per unit time. If the wave flow has some energy, it should have some linear momentums as well. Any obstacle on the way of such wave flow generates reflection and/or dissipation of its energy. Hence, interaction with some obstacle changes the power flux of this wave stream. Any change of the power flux leads to change of its linear momentum. Change of the linear momentum – at interaction with some obstacle – defines appearance of the ARF over a surface of this obstacle. Hence, it is just the time to take a look on well known expression for the radiation force in theoretical physics [3], p. 997

$$ARP = I/c \qquad (3)$$

where: I is the power flux and c is a wave velocity. Expression (3) describes a case of full absorption of incident waves at normal incidence on the flat surface of the obstacle. In case of full reflection we see increasing of the radiation force in 2 times (at normal incidence) [3], p. 997. May it be applied in acoustics? No obstacles, it should be applied there … Hence we see the second important model of the ARF in acoustics.

There are few more words about this second model of the ARF: description of this model does not contain terms “nonlinear” or “nonlinearity”. There are applied only linear properties of the medium to get expression (3). The ARF in the expression (3) **does not depend on passed distance** (if medium does not have attenuation). The ARF is just linear function of I (quadratic function of the dynamic pressure amplitude). There is obvious question: which model of the ARF could be applied for wave flow in nonlinear media? It is discusses in the section 4.

2. EQUIPMENT AND METHODS

All measurements were done in water tank at room conditions and with high intensity ultrasound: dynamic pressure amplitude was 4 MPa and higher; work frequencies were 3.1 MHz and 4.3 MHz. Transducer 3.1 MHz had the focal distance F = 31 mm, transducer 4.3 MHz had F = 28 mm. Ultrasonic transducers were built in closed Aluminum housing (Ultrasonic S-Lab). Each transducer has efficiency 50% – 60%. It means: 50 – 60% of feeding electric power converts into a flow of radiated ultrasonic waves. Diameter of active radiating area is 19 mm – for both transducers. The ARF meter was done as a low frequency hydrophone with flat metal sensitive area (diameter 12 .7 mm, condition of full reflection). There was acoustic attenuator in the ARF meter to protect sensitive element (protect from destruction by HIFU). The ARF meter was designed and built in the Ultrasonic S-Lab. The meter has electric low pass filter (cut-off frequency ~ 100 kHz) for protection of the oscilloscope from electric signals with frequencies higher 100 kHz.

Electric signal for the HIFU transducers was going from the digital function generator Agilent 33220A to a power amplifier ENI 325LA (25 W) and, further, to the HIFU transducer in the water tank. Each transducer has inner matching circuit to get electric impedance 40 – 65 Ω at its work frequency – to get good electric matching with the power amplifier. Output signal of the ARF meter was measured with digital oscilloscope Tektronix 1012.

HUFU transducer and the ARF meter were mounted in 3-D scanning system. Axial scanning (along acoustic axis of the transducer) was done at distances L from 0.7 F to 1.4 F, where F is the focal distance of the HIFU transducer.

All measurements of the ARF were done in pulse mode. The ARF meter was under incidence of pulse acoustic signal like on a Fig. 1-A. Such ultrasonic pulse signal had area with growing dynamic pressure amplitude – at the frontal edge (~15 periods), and area of the pulse with decaying dynamic pressure amplitude (~ 15 periods) – at the back edge. Output electric signal from the ARP meter is shown on the Fig. 1-B. There is positive pulse in time of growing dynamic pressure amplitude, and negative pulse - in time of decaying of this dynamic pressure amplitude. At frequency 3.1 MHz duration of such frontal pulses was ~ 4.8 µs. At frequency 4.3 MHz it was ~ 3.5 µs. Correct ARF signal is between these frontal pulses. Total duration of ultrasonic pulse, containing 60 periods is ~19 µs – for work frequency 3.1 MHz, and ~ 14 µs – for work frequency 4.35 MHz.

Water tank was a container with reduced echo-signals from its walls: the walls were covered by thick layers of high absorbing material – polyurethane.

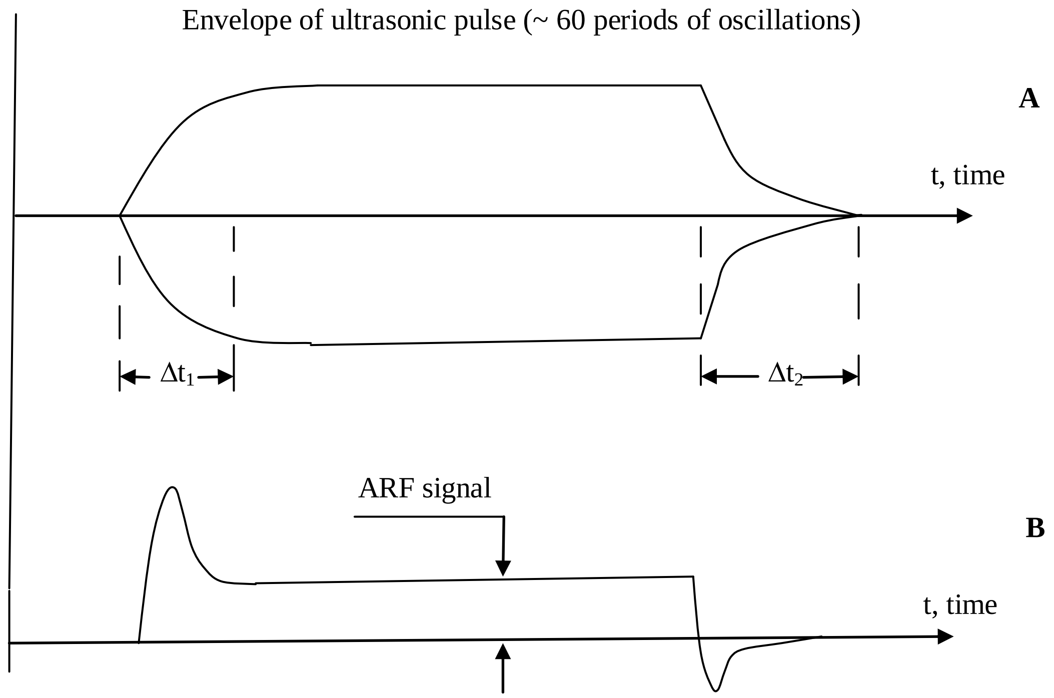

Fig. 1-A. Ultrasonic pulse (envelope) contains ~ 60 periods of oscillations. Δt_1 is an area with growing dynamic pressure amplitude, Δt_2 is an area with decaying pressure amplitude.

Fig. 1-B. Output electric signal from the ARF meter. There are local pulses in the areas of growing and decaying of dynamic amplitude. Both these local pulses should not be taken into account at the measurements of the ARF.

3. MEASURED DATA

First step was to check quadratic dependence of the ARF signal on dynamic pressure amplitude. Results of this check you can see below on the Fig. 2. Quadratic dependence would be direct confirmation of accuracy of used meter.

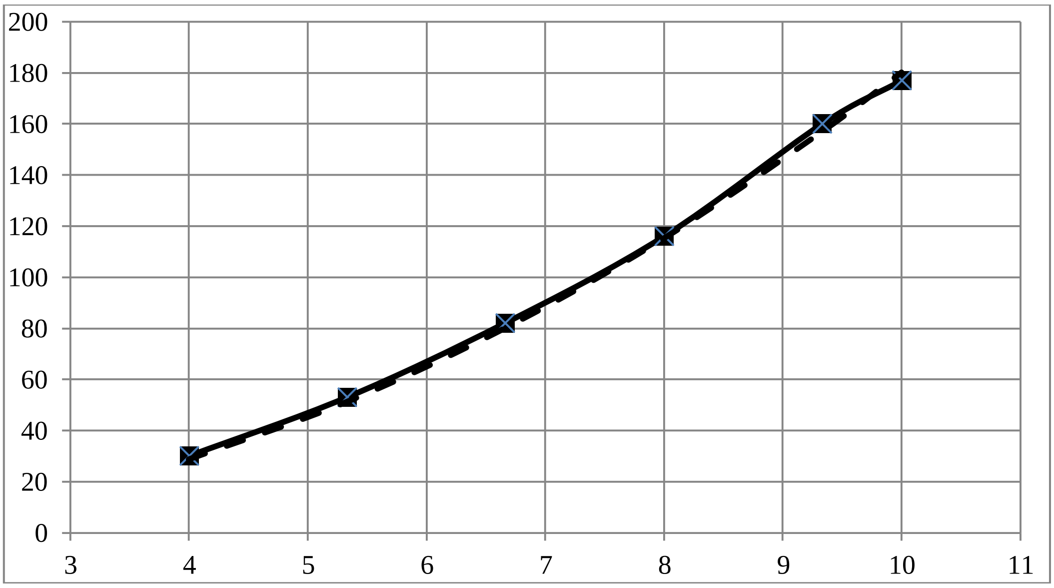

Fig. 2. Output signal of the ARF meter as function of dynamic pressure amplitude. Amplitude of the dynamic pressure, in MPa, is over the horizontal axis. Output signal of the ARF meter, in mV, is over the vertical axis. Dependence of the ARF signal on dynamic pressure amplitude is depicted by solid black line. Dependence of dynamic amplitude in the second power is depicted by dotted black line. Coefficient in this last dependence was adjusted to get full coincidence with solid black line at maximal dynamic pressure amplitude (at p_m = 10 MPa).

Measurements were done at work frequency 4.35 MHz. ARF meter was located in the focal spot of the HIFU transducer (normal incidence, full reflection). It needs to add, that dynamic pressure was measured in unbounded water medium. Dynamic pressure at the surface of the ARF meter is in two times higher, due to full reflection over this surface. Changes of the dynamic pressure amplitude were done by changing the feeding electric signal for the HIFU transducer. So, Fig. 2 demonstrates: output signal of this new ARF meter is quadratic function of dynamic pressure amplitude – like it should be expected for the ARF.

Next step: measurements of experimental dependence the ARF on distance "transducer – meter" (L) at condition: normal incidence and full reflection. Axial distance L was changed from 20 mm to 38 mm. Cross-section of ultrasonic flow was less than sensitive area of the ARF meter at all these changes of L. Focal spot of the HIFU transducer was at L = 28 mm. These measurements were done at 2 different intensities of the ultrasonic flow. On the first glance, ARF should not depend on the distance L. But experimental data (below, on the Fig. 3) demonstrate growing of the ARF at increasing of the distance L. Discussion of this new experimental result is below in the section 4.

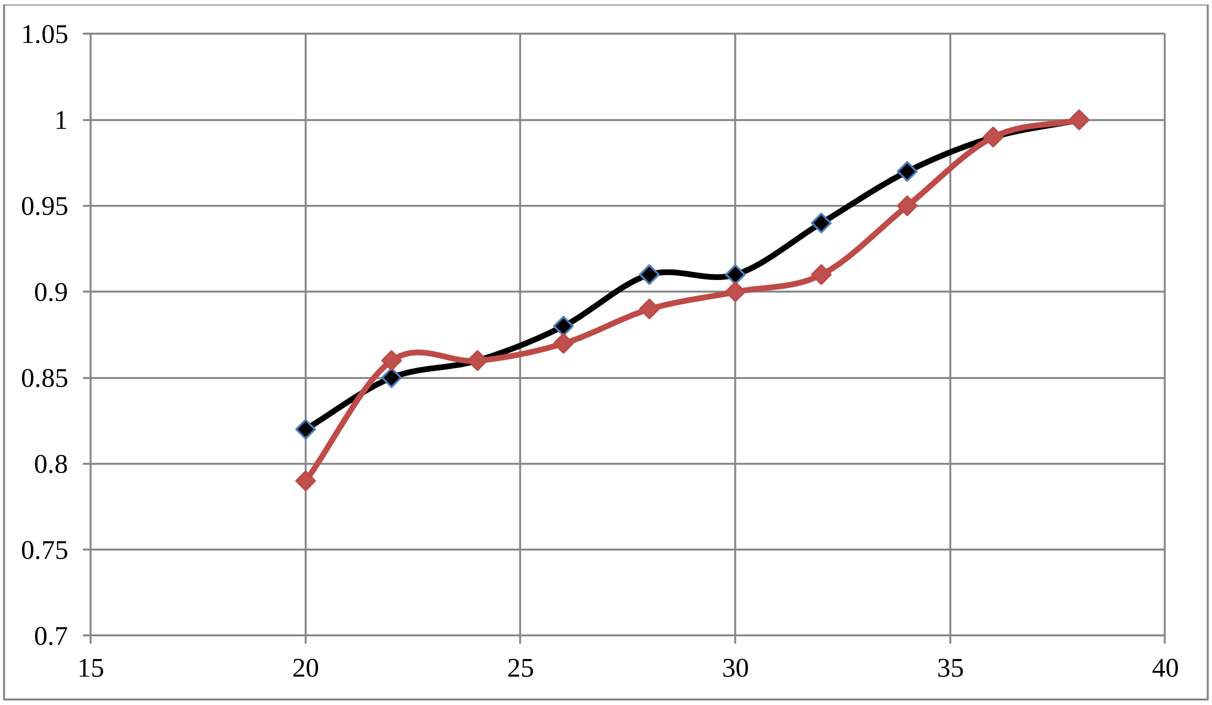

Fig. 3 Dependence of the ARF on distance L between the transducer and the ARF meter (normal incidence and full reflection). Measurements were done at frequency 4.35 MHz, focal spot was at L = 28 mm. Measured data at moderate intensity (4 MPa at the focal spot) are shown by solid black line. Measured data at higher intensity (10 MPa at the focal spot) are shown by solid brown line. Actually, we see plots of normalized measured data: ARF/ARF(Lmax). Distance in mm is on the horisonatl axis. Normalized data for the ARF are on the vertical axis.

Next step: measurements of angular dependence of the ARF. Measurements were done at the focal distances of both HIFU transducers – with work frequencies 4.35 MHz and 3.1 MHz. Actually, measurements were done at 3 different values of the incident angle: 0^0, 30^0, and 60^0 (0^0 is a case of the normal incidence). The ARF at 30^0 is 0.75 ARF were measured at normal incidence – for both frequencies. The ARF at 60^0 is ~ 0.5 of the ARF at the incident angle 0^0 – for both frequencies.

4. DISCUSSION

Earlier (in the Introduction) it was noted about existence of 2 possible (and different) models of the ARF phenomenon: nonlinear properties of real acoustic media [1, 2] and possible existence of linear momentum in acoustic wave flow. Each model looks like correct one. Which model should be applied in reality?

Let us consider one more important detail. There are existing meters of power for ultrasound. How do they work: in a frame of which ARF model? If we take a look at some documents, like [4] – for acoustic power meters from company Ohmic – we can get clear and direct answer: real measurements are going with expression (3) – this model is based on the change of the linear momentum of ultrasonic flow at its interaction with the reflecting (or absorbing) targets. It is model # 2 for the ARF and this model does not take into account nonlinear distortions of acoustic waves (something connected with corresponding models for the ARF in above noted books [1, 2]). These data demonstrate necessity of the model # 2 to describe the ARF phenomenon in acoustic media.

Our measured data – see Fig. 3 above – demonstrate growing of the ARF with distance between the transmitter and the ARF meter in a water (it is good example of nonlinear acoustic medium with very low attenuation). More ever, there are same slops on plots for dynamic pressure amplitudes 4 MPa and 10 MPa. Hence, there is growing of the DC component (harmonic # 0) of ultrasonic waves in real acoustic media. Hence, growing of the DC component with the passed distance is in analogy with growing of the nonlinear distortions on passed distance – see book [2], page 113. Hence, the model # 2 is not able to describe of the ARF in full. Hence, the ARF could be considered as a sum of contributions from the model # 2 and from the model # 1.

But the model # 1 in books [1, 2] looks like not completed: we can not see dependence of the ARF on the passed distance. But if reader has some background in solution of nonlinear equations, he can expect following. If acoustic wave flow travels through nonlinear acoustic medium, it can not have same distortions over its way. Distortions should grow with growing passed distance. Usual approach in numerical methods: passed distance can be considered as series of short intervals with numbers 1, 2, …N. Researcher should build solution of the nonlinear equation in this first interval with initial data: harmonic incident signal (signal without any distortions). Solution in the first interval will demonstrate appearance of some distortions. These data should be used as the initial data to build solution in the second interval. Hence, distortions in the second interval will be larger the distortions in the first interval. And so on. These distortions include all harmonics of the incident acoustic signal: with indexes 0, 1, 2, … It should be done to get correct expression for the ARF as some function of passed distance.

When existing model # 1 will be completed, we, probably, should apply this model in following way. Any flow of ultrasonic waves has some DC component just after its radiation – in according to above model # 2. But this DC component is the growing function with increasing of passed distance. This increasing of the DC component can be correctly described in a frame of completed model # 1. From mathematical view point: initial data for calculation of the DC component, as function of passed distance, should be started from the DC component with above expression (3).

Last conclusion looks like pure mathematical feature of ultrasonic waves in nonlinear acoustic media. But direct measurements of the ARF is wide known method for measurements of power flux in ultrasonic wave flows. There are many devices for such measurements. Almost all these devices provide measurements on the base of the model # 2 only – without additional contribution to the ARF from the model # 1. It means that all measurements on the base of the model # 2 only provide too high results for the power flux – with positive error 10% - 30 %. Probably, this point deserves serious attention.

5. QUESTIONS AND ANSWERS

Question. What can you say about the ARF at interaction of power ultrasonic waves with thin plastic film without attenuation? At normal incidence?

Answer. Thank you for such question. Contribution into the ARF from both components will be close to zero, because there should be no change of the power flux at transmission through such plastic film. Hence, there will not any change of the linear momentum of the ultrasonic wave flow. I did such experiment. The ARF at the normal incidence on thin plastic film with very low attenuation was very-very weak. There were low coefficients for the reflection and the absorption.

Question. Is it possible to use low frequency hydrophone as a meter of the ARF?

Answer. It should be special hydrophone. First of all, it should have protection of a sensitive element of the hydrophone from power ultrasonic signal – to protect it from destruction. We use acoustic attenuator for it. Plus, there should be low pass electric filter to protect output signal from signals with high work frequency. It would be better to use low pass filter. We applied low pass filter with cut-off frequency ~ 100 kHz. My current report does not contain detailed description of our ARF power meter, I am sorry. You can apply to Ultrasonic S-Lab for such information, prices, and so on.

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