Nonlinear Wave Phenomena in Gases and Liquids

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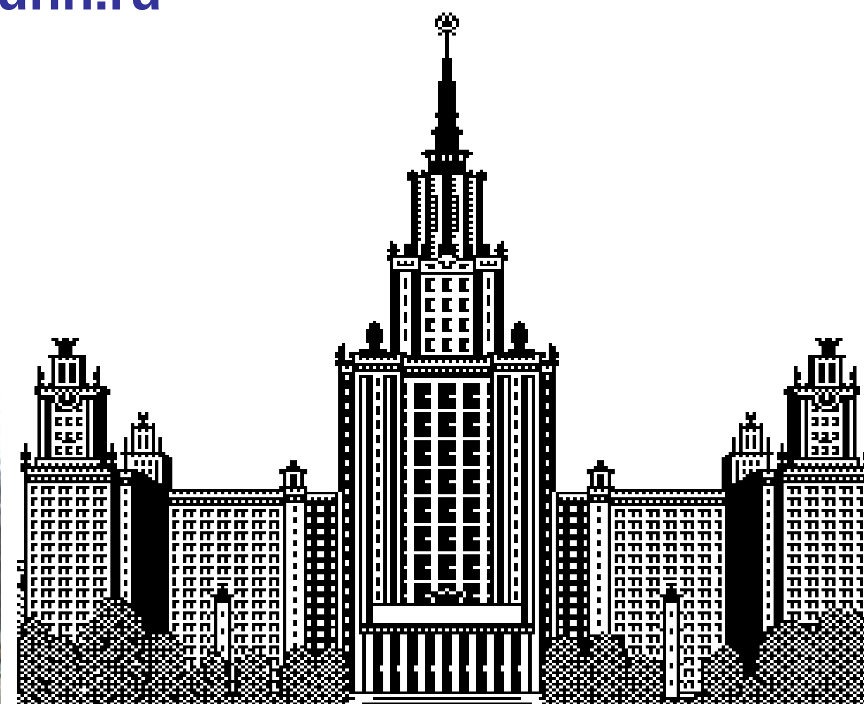


TOPICS

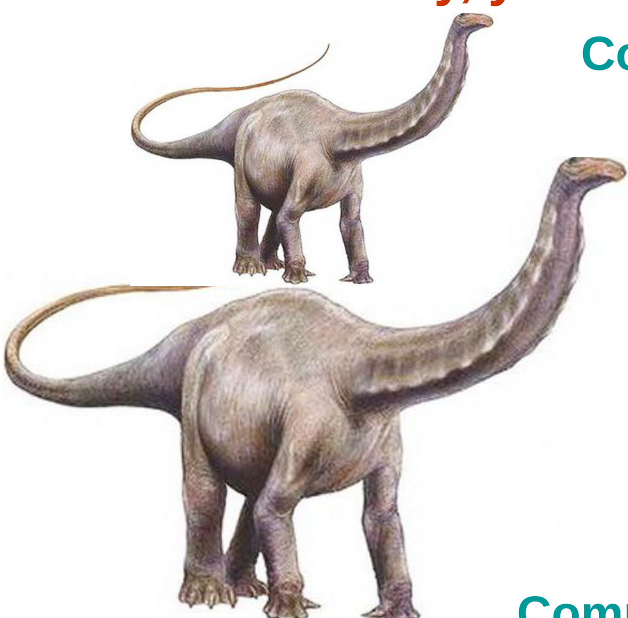
1. The difference between (i) strong nonlinearity and (ii) strongly expressed weak nonlinearity is discussed. Both are responsible for waveform distortion, shocks formation, and corresponding broadening of frequency spectra.
2. Classical nonlinear phenomena significant from the viewpoint of aeroacoustics are reviewed. Among them are transformations of different noise spectra, and noise control by high-intensity signal. After review, following problems will be discussed:
3. Sonic booms in turbulent atmosphere.
4. New mathematical models including nonlinear integro-differential equations (IDE). IDE describe regular and noise waves in atmosphere where the spectrum of relaxation times of different gases should be considered for correct description of shock waves
5. Standing waves in gas-filled resonators
6. Nonlinear sound absorbers

Name of this workshop is **"Computational Experiment in Aero-acoustics"**. Evidently, key word here is **"Computational"**

The title of our talk is **"Nonlinear Wave Phenomena in Gases and Liquids"**. Key words here are **"Nonlinear Phenomena"**

Somebody may think, that this talk is out of line with this meeting. But such viewpoint is incorrect. This can be easily proved.

Really, you can read CEAA from left to right:



Computational

Experiment

in

Aero

Acoustics

C E A A

Computers

Excepting

Acoustics

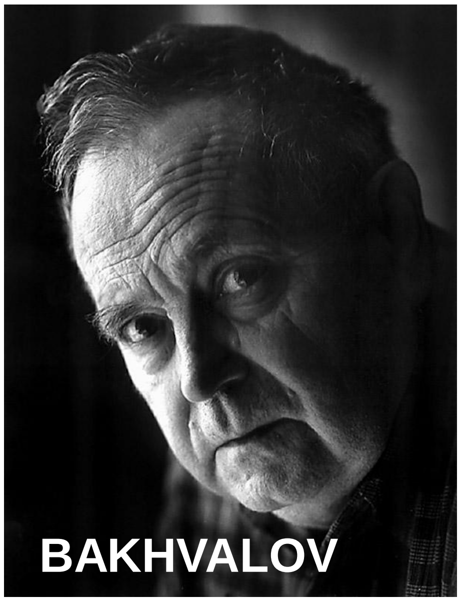
Analytical

But you can also read this abbreviation in opposite directioin - from right to left:

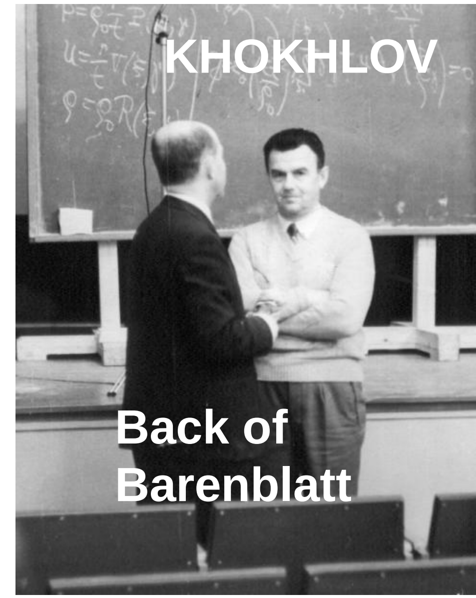
Such interpretation shows that this talk completely corresponds to main topic of this remarkable event

However, numerical studies of nonlinear phenomena really go on more than 40 years

"Computer" collaboration between mathematicians and physicists was initiated by academicians N.S.Bakhvalov and R.V.Khokhlov.



Their first meeting took place on 20 March 1974, in the office of Khokhlov, who was that time the Rector of Moscow University. Khokhlov, Bakhvalov, Rudenko, and Zhileikin participated in that meeting.



During 1974-1993: codes for БЭСМ-6 and IBM PC/AT-286 were developed , 50 papers were published. Application packages were created: "NACSI" (1990) (Nonlinear Acoustics – Computer Simulation), and "SB"(Sonic Boom). (1993).

1. **Noviklov, Rudenko, Timoshenko "Nonlinear Underwater Acoustics". Sudostroenie, 1981; NY, Amer.Inst.of Physics, 1987.**
2. **Bakhvalov, Zhileikin, Zabolotskaya "Nonlinear sound beams". Nauka, 1982.**
3. **Vasil'eva, Karabutov, Lapshin, Rudenko "Interaction of 1D waves in diapersionless media" MSU Press, 1983.**

There were performed first numerical studies of nonlinear waves in acoustics. Now computer studies predominate everywhere because of 2 reasons:

1. **All simple problems are already solved, and only few experts can solve analytically some new complicated problems.**

2. **Nonlinear acoustics was a field of fundamental research (during about 1950-1980). Now it belongs rather to applied science and even to engineering.**

Main applications are connected with medical ultrasound, underwater acoustics, Earth sciencies, industrial NDT and aeroacoustics.

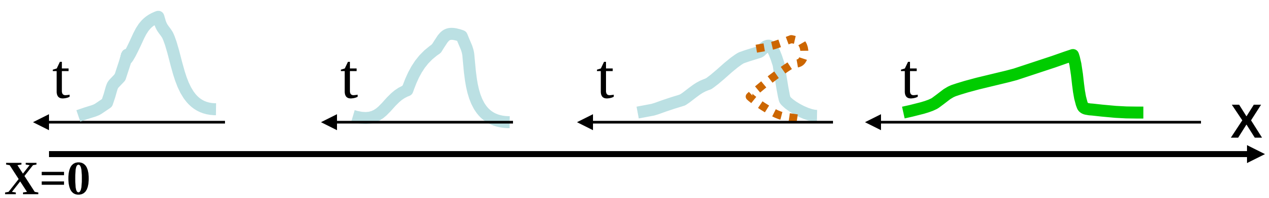
However, for better understanding of new nonlinear phenomena it is desirable, at least at the first stage, to use analytical approaches. I will try to give a brief review of some phenomena which may be interesting or seem to be promising for applications.

1. Aeroacoustics deals with both Strongly Nonlinear Waves (SNW) and Weakly Nonlinear Waves (WNW)

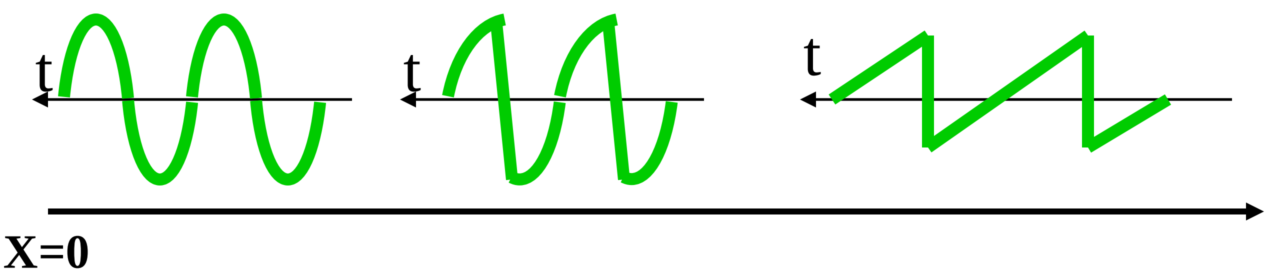
WNW can demonstrate, however, strong distortion of their shape and spectrum. What is the difference between these two types of wave?

Up to now, mainly WNW have been studied by Nonlinear Wave Theory.

Typical strongly expressed effects of weak nonlinearity are:



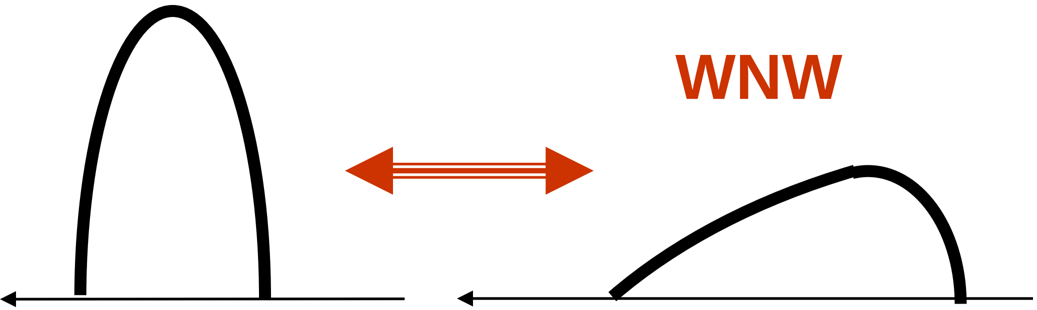
transformation of smooth single pulse to a triangular profile with a leading shock front;



transformation initially harmonic wave to sawtooth wave with one shock per period.

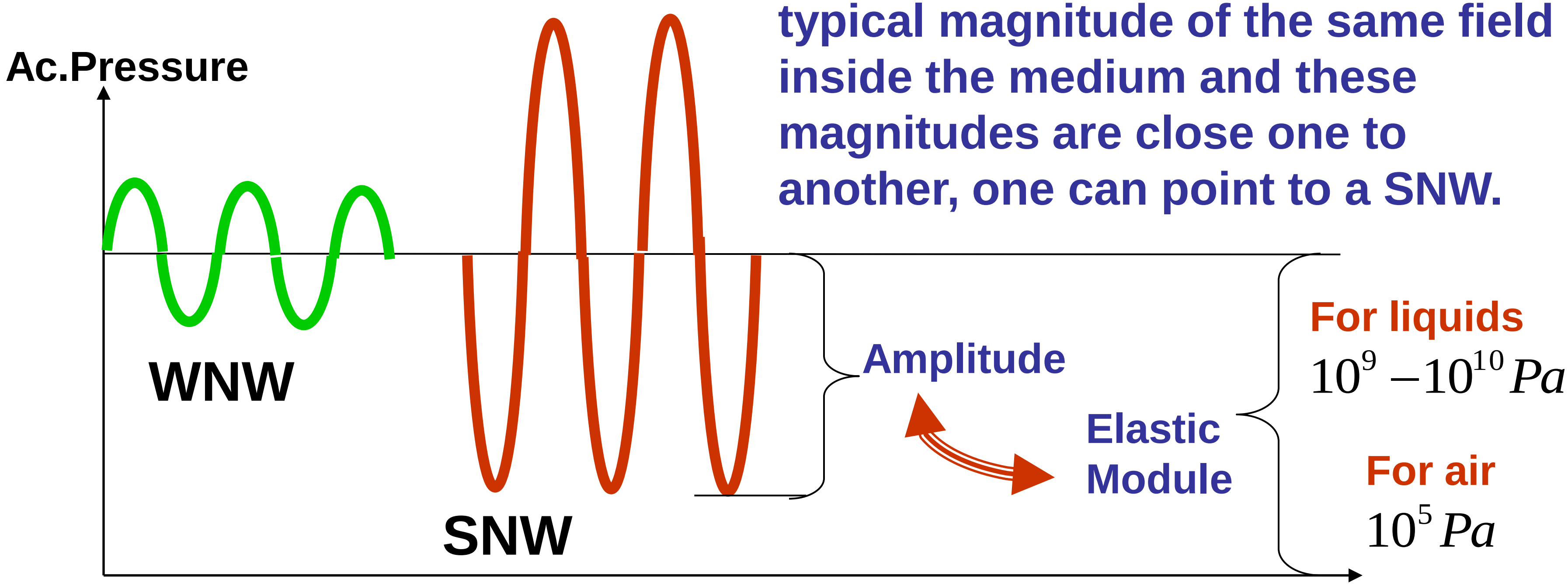
When a shock front appears at a distance of $10^2 - 10^3$ wavelengths, nonlinearity is weak but strongly expressed. Acoustic pressure here is much less than 1 atm. In water WNW has amplitude less than 23000 atm

The question: if the wave is said to be weak or strong - it is in comparison with what ?



If the wave (spectrum, shape) is compared with itself at initial moment of time, and strong changes are observed, one can point to a WNW.

If the wave is compared with a typical magnitude of the same field inside the medium and these magnitudes are close one to another, one can point to a SNW.



In the study of WNW, the equation of state (or determining equation) can be expanded in a power or functional series. First example is the expansion of the adiabatic equation of state in powers of density and pressure disturbances in the vicinity of equilibrium state (p_0, ρ_0) :

$$p' = p_0\left(\frac{\rho_0 + \rho'}{\rho_0}\right)^{\gamma} = p_0 + c_0^2\rho_0\left[\frac{\rho'}{\rho_0} + \frac{\gamma-1}{2}\left(\frac{\rho'}{\rho_0}\right)^2 + \frac{(\gamma-1)(\gamma-2)}{6}\left(\frac{\rho'}{\rho_0}\right)^3 + \ldots\right]$$

More general is the the Volterra-Frechet functional series expansion:

$$p' = c_0^2\int_0^{\infty} K(\tau)\rho'(t-\tau)d\tau + \int_0^{\infty}\int_0^{\infty} K^{(2)}(\tau_1,\tau_2)\rho'(t-\tau_1)\rho'(t-\tau_1-\tau_2)d\tau_1 d\tau_2 + \ldots$$

However, such expansions cannot be used in 3 cases.
(i) if the “equation of state” contains a singularity
(ii) Secondly, if series are divergent for strong fields
(iii)Thirdly, if the linear term is absent and nonlinearity dominate

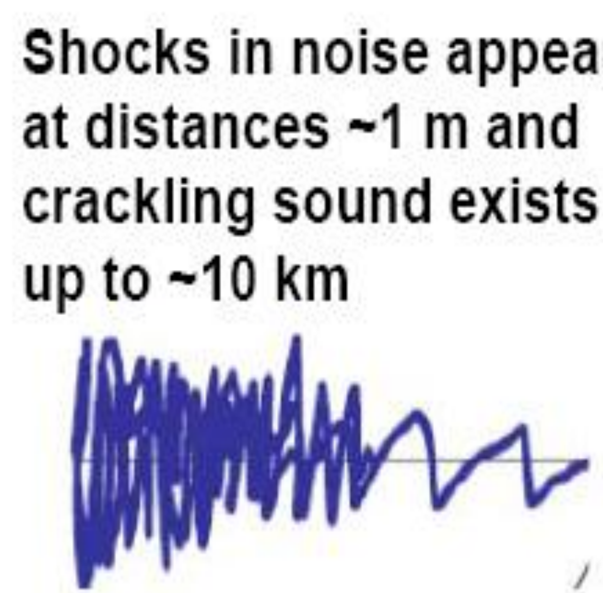
Examples of 3 types of strongly nonlinear vibration systems

$$\frac{d^2x}{dt^2} + \omega_0^2 x_0 \frac{d}{dx}|x| = 0, \qquad \frac{d^2x}{dt^2} + \frac{\omega_0^2 x}{\sqrt{1-x^2/a^2}} = 0, \qquad \frac{d^2x}{dt^2} + \frac{\omega_0^2}{x_0^2}x^3 = 0$$

Examples of 3 types of strongly nonlinear waves

The 1st is the Burgers-type equation, 2nd is the Earnshow equation, and 3rd is generalized Heisenberg equation. All three models have exact solutions with important physical meaning.

$$\frac{\partial u}{\partial x} = \frac{1}{2}\frac{\partial}{\partial t}\left(|u|u\right) + \Gamma\frac{\partial^2 u}{\partial t^2}, \qquad \frac{\partial^2 \xi}{\partial t^2} = \frac{c_0^2}{\left(1+\partial\xi/\partial x\right)^{2\varepsilon}}\frac{\partial^2 \xi}{\partial x^2}, \qquad \frac{\partial^2 \zeta}{\partial t^2} = \frac{\beta}{3}\frac{\partial^2 \zeta^3}{\partial x^2}$$

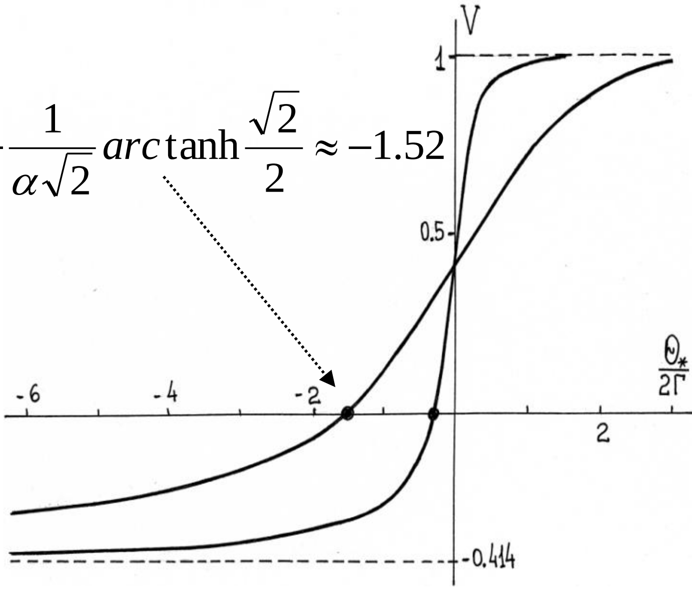


Sonic boom wave near supersonic aircraft and high-power noise at launching of big missiles are examples of SNW

Exactly solvable model: quadratically-cubic Burgers Eq. with the singularity

$$\frac{\partial V}{\partial Z}=\frac{1}{2}\frac{\partial}{\partial\theta}\left(|V|V\right)+\Gamma\frac{\partial^2 V}{\partial\theta^2}$$

$$\frac{\theta_0}{2\Gamma}=-\frac{1}{\alpha\sqrt{2}}\,arc\tanh\frac{\sqrt{2}}{2}\approx-1.52$$

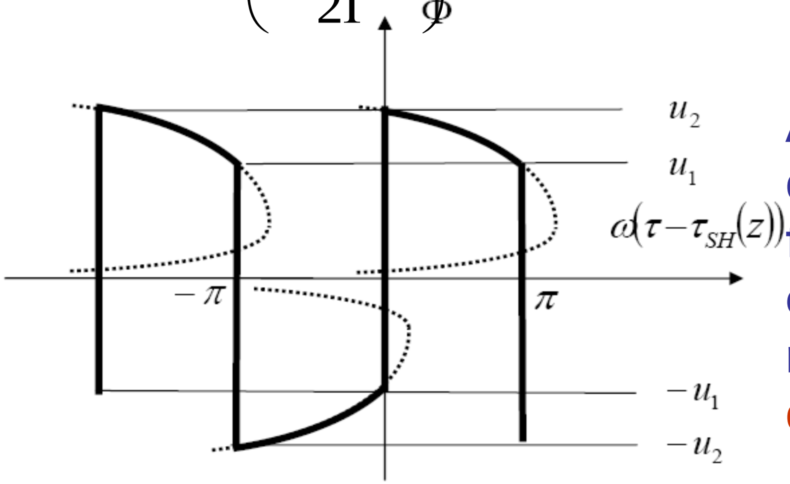


Linearity substitution: $V=2\Gamma\,\mathrm{sgn}(V)\frac{\partial}{\partial\theta}\ln U$

One of Stationary waves – stable shock of compression

$$V=\frac{\alpha^2\left(\frac{\theta_*-\theta_0}{2\Gamma}\right)}{1-\alpha\left(\frac{\theta_*-\theta_0}{2\Gamma}\right)},\quad -\infty<\theta_*<\theta_0,\qquad V=\alpha\left[1+\sqrt{2}\tanh\left(\alpha\sqrt{2}\,\frac{\theta_*}{2\Gamma}\right)\right],\quad \theta_0<\theta_*<\infty$$

$$\theta_*=\omega\left(\tau-\tau_{SH}(z)\right)\qquad \alpha\equiv\left(\sqrt{2}-1\right)$$



As distinct from usual "saw-tooth" wave in quadratic medium, here the have trapezoidal form, instead of triangular. Each period contains 2 shocks: compression and rarefaction. The last type does not exist in quadratic media.

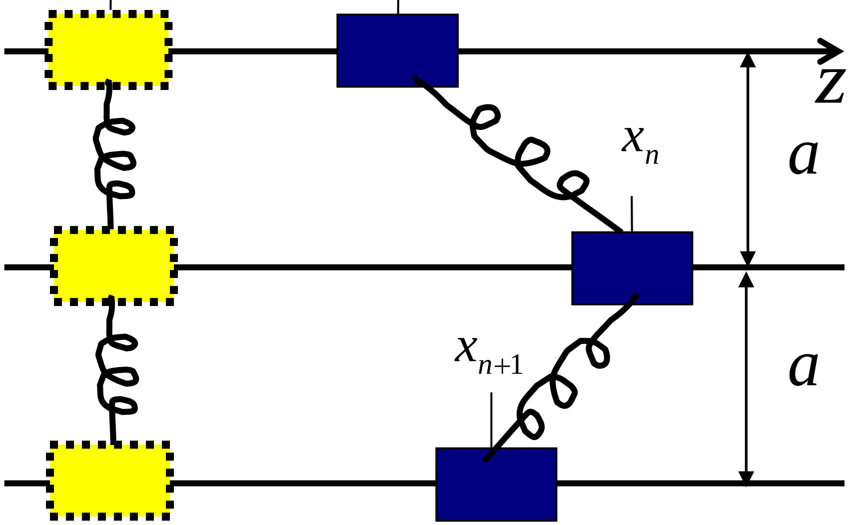
SNW of the 3rd type: there is no linear term

Consider a chain of masses. Each moves along a parallel bar placed at the same distance from one another. If in equilibrium state all springs are not tensed, the linear regime does not exist.

$$\frac{d^2 x_n}{dt^2} = -\frac{k}{2a}\left[\left(x_n - x_{n-1}\right)^3 - \left(x_{n+1} - x_n\right)^3\right]$$

The equation of motion of a mass

$x = 0$ $\quad x_{n-1}$



If all masses except n=m are fixed, chain reduces to a single ordinary equation:

$$\frac{d^2 x_m}{dt^2} = -\frac{k}{a} x_m^3$$

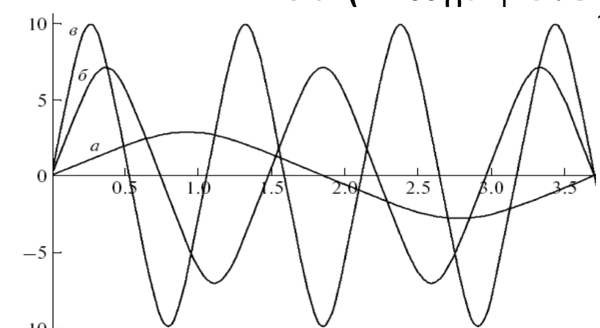
Normalized form:

$$X = x/a, \;\; \tau = \omega_0 t \qquad \frac{d^2 X}{d\tau^2} + X^3 = 0$$

Heisenberg W. *Zur Quantisierung nicht-linearer Gleichungen.* Nachr. Acad. Wiss. Goettingen. 1953. V. IIa. No.8. P.111-127

Solution expressed through Jacobi elliptic functions is: $X = A \cdot sd\left(A\omega_0 t \mid 0.5\right)$

$$X = A\frac{16\pi^{3/2}}{\Gamma^2(1/4)}\sum_{m=1}^{\infty}(-1)^{m+1}\frac{\exp\left(-\pi(m-1/2)\right)}{1+\exp\left(-2\pi(m-1/2)\right)}\sin\left[(2m-1)\frac{2\pi^{3/2}}{\Gamma^2(1/4)}A\omega_0 t\right]$$



Fourier series expansion contains olny odd harmonics

The period decreases with increase in amplitude.

Higher harmonics are weak !

In the continuum model the differential-difference eq. reduces to a nonlinear partial differential equation:

$$\frac{\partial^2 \zeta}{\partial t^2} = \frac{\beta}{3}\frac{\partial^2 \zeta^3}{\partial z^2}$$

Here $\zeta = \partial x / \partial z$ is the deformation, and $\beta = \frac{3k}{2m}a^2$

Continual generalization of W.Heisenberg Eq.

Interestingly, this equation has a solution describing standing waves, but the traveling waves appear only for springs which are tensed in equilibrium. The propagation velocity increases with increase in tension.

If springs of mechanical chain are slightly stretched and have softening nonlinear characteristics, the equation is:

$$\frac{\partial^2 x}{\partial t^2} - c^2 \frac{\partial^2 x}{\partial z^2} = -\beta\left(\frac{\partial x}{\partial z}\right)^2 \frac{\partial^2 x}{\partial z^2}$$

This equation has some remarkable properties. In particular, it can be linearized by Legendre transformation: $t = T\left(\xi = \frac{\partial x}{\partial z}, \eta = \frac{\partial x}{\partial t}\right)$

$$\frac{\partial^2 T}{\partial \xi^2} = \left(c^2 - \beta \xi^2\right)\frac{\partial^2 T}{\partial \eta^2}$$

This Eq. transforms from hyperbolic to elliptic type like Euler-Tricomi equation

Phase velocity of quasi-harmonic wave is $v_{PH} = \sqrt{c^2 - \beta |A_0|^2 / 6}$

Consequently, self-trapping comes at amplitudes $|A_0|^2 > 6c^2/\beta$

Moreover, this "self-stopped" wave traps all other weak waves propagating trough this spatial region

Accretion on a Singularity of strongly nonlinear wave

Singular solutions have well-known Eqs of the theory of nonlinear waves.

Example: usual Burgers Eq.
Let it be valid for SNW

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial z}=\Gamma\frac{\partial^2 V}{\partial z^2}$$

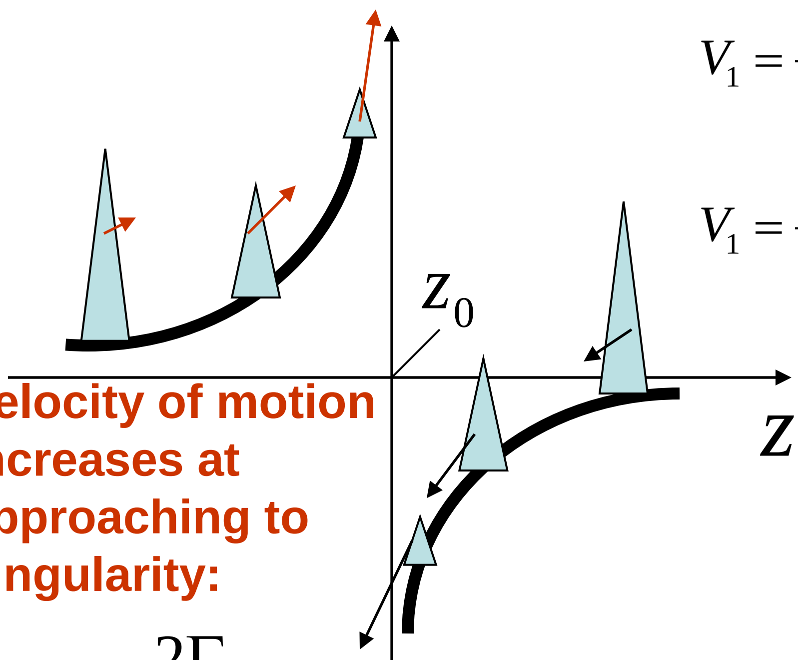
Some of its singular solutions:

$$V=-\frac{2\Gamma}{z-z_0},\quad V=-\tan\frac{z-z_0}{2\Gamma}$$

Near the singularity weak disturbances are described by formulas:

$$V_1=\frac{z-z_0}{\sqrt{(z-z_0)^2+4\Gamma t}}\Phi\left[z_0+\sqrt{(z-z_0)^2+4\Gamma t}\right],\quad z>z_0,$$

$$V_1=\frac{x_0-x}{\sqrt{(z-z_{00})^2+4\Gamma t}}\Phi\left[z_0-\sqrt{(z-z_0)^2+4\Gamma t}\right],\quad z<z_0.$$



Velocity of motion increases at approaching to singularity:

$$v=\frac{2\Gamma}{z_0-z}$$

This process is similar to the accretion on the black hole.

Singularities behave like particles. They are stable and can interact with each other

Analogous solution has KdV and other well-known models:

$$V=\frac{12\Gamma}{(z-z_0)^2}\qquad \frac{\partial V}{\partial t}+V\frac{\partial V}{\partial z}=\Gamma\frac{\partial^3 V}{\partial z^3}$$

2. Classical phenomena of Statistical Nonlinear Acoustics

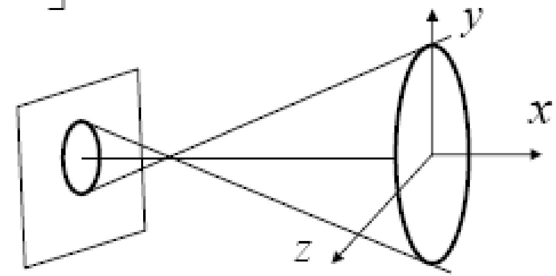
$$\frac{\partial}{\partial\tau}\left[\frac{\partial p}{\partial z}-\frac{\varepsilon}{c_0^3\rho_0}\,p\,\frac{\partial p}{\partial\tau}\right]=\frac{c_0}{2}\Delta_\perp p$$

Khokhlov-Zabolotskaya Eq.

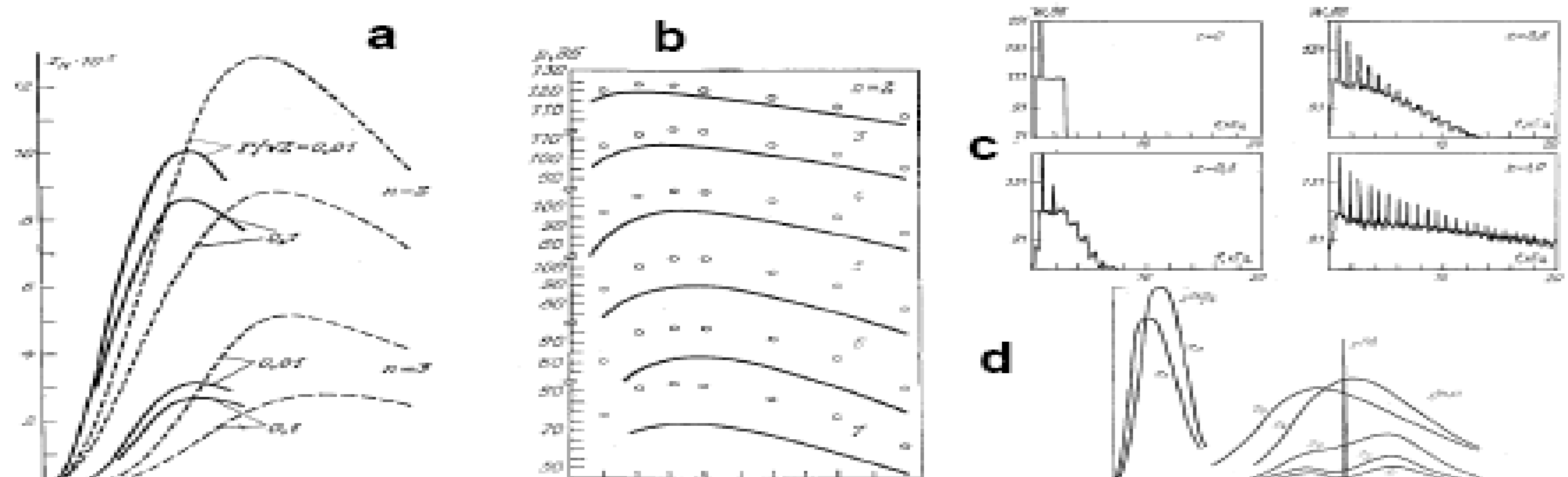
"General" evolution equation for nonlinear waves is

$$\frac{\partial}{\partial t}\left[\frac{\partial u}{\partial x}-u\frac{\partial u}{\partial t}-\frac{\partial^2}{\partial t^2}\int_0^\infty K(s)u(t-s)ds\right]=\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}=\Delta_\perp u \tag{1}$$

Here t is the time, and x, y, z - Cartesian coordinates. The coordinate x coincides with the preferred orientation of the wave propagation. Other (transversal) coordinates are introduced in the cross-section of a beam.

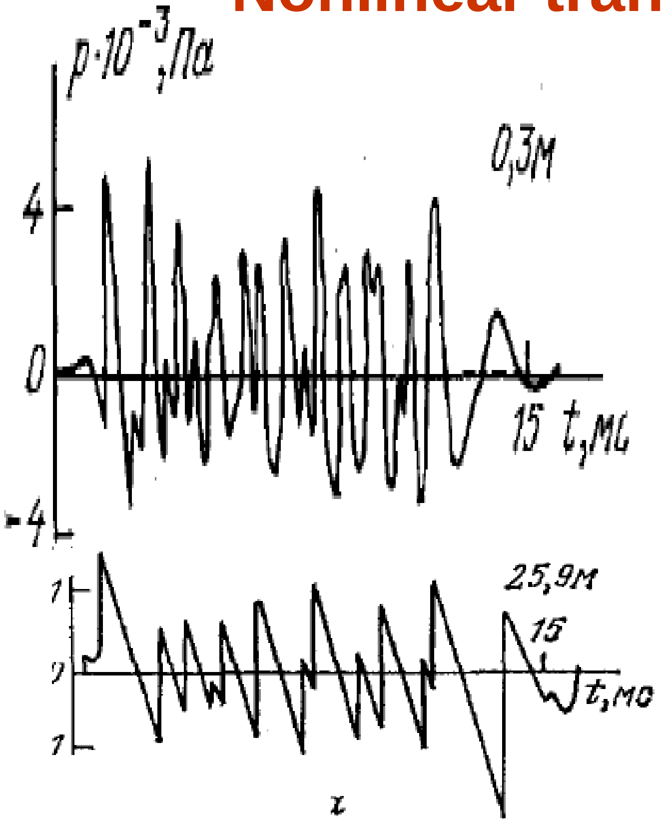


(a) Intensities of 2-nd и 3-rd harmonics of narrow-band noise (solid curves) and tone signal of equal intensity (dashed curves). (b) – is the experiment. Interactions of wide-band noise with tone signal (c). Spectral fragment up to higher harmonics (d)



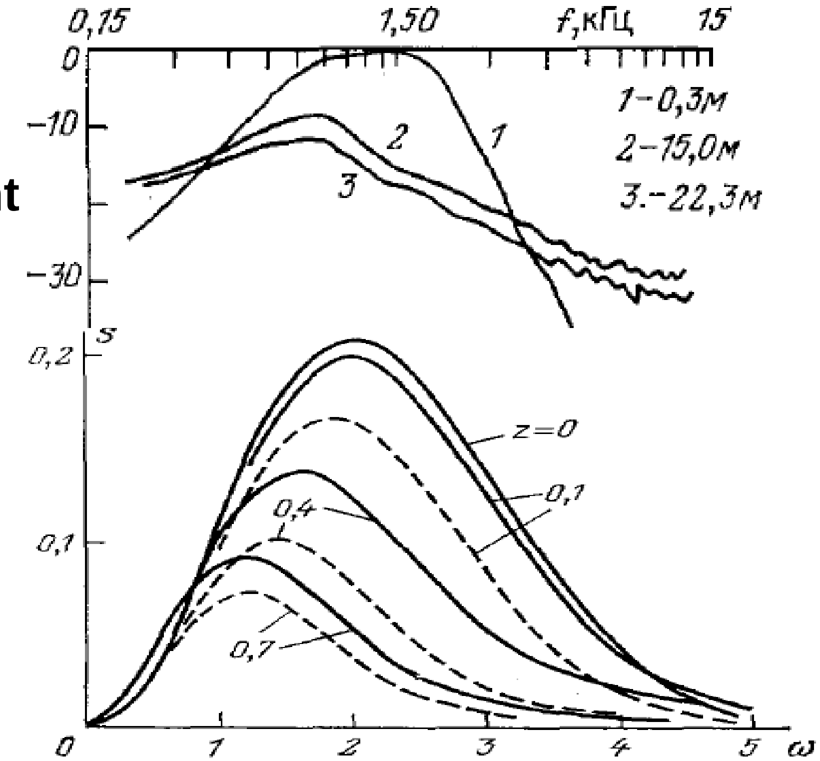
In Figs. c, d Great number of harmonics appear. Wide-band noise spectrum is reproduced at the left and right of each line, therefore"white noise" grows rapidly.

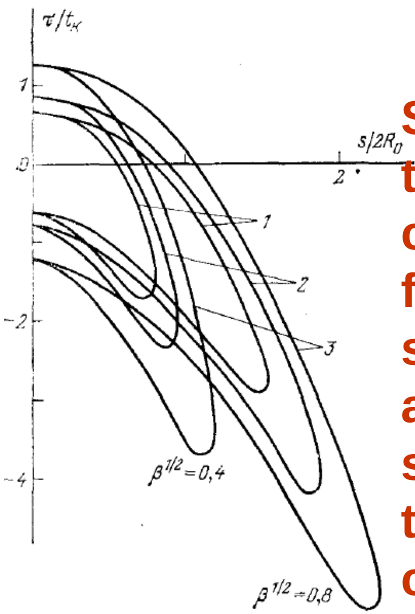
Nonlinear transformation of high-intensity noise



Experiment

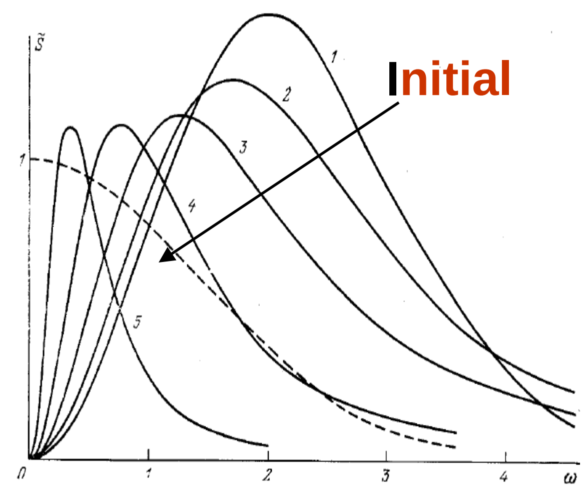
Theory

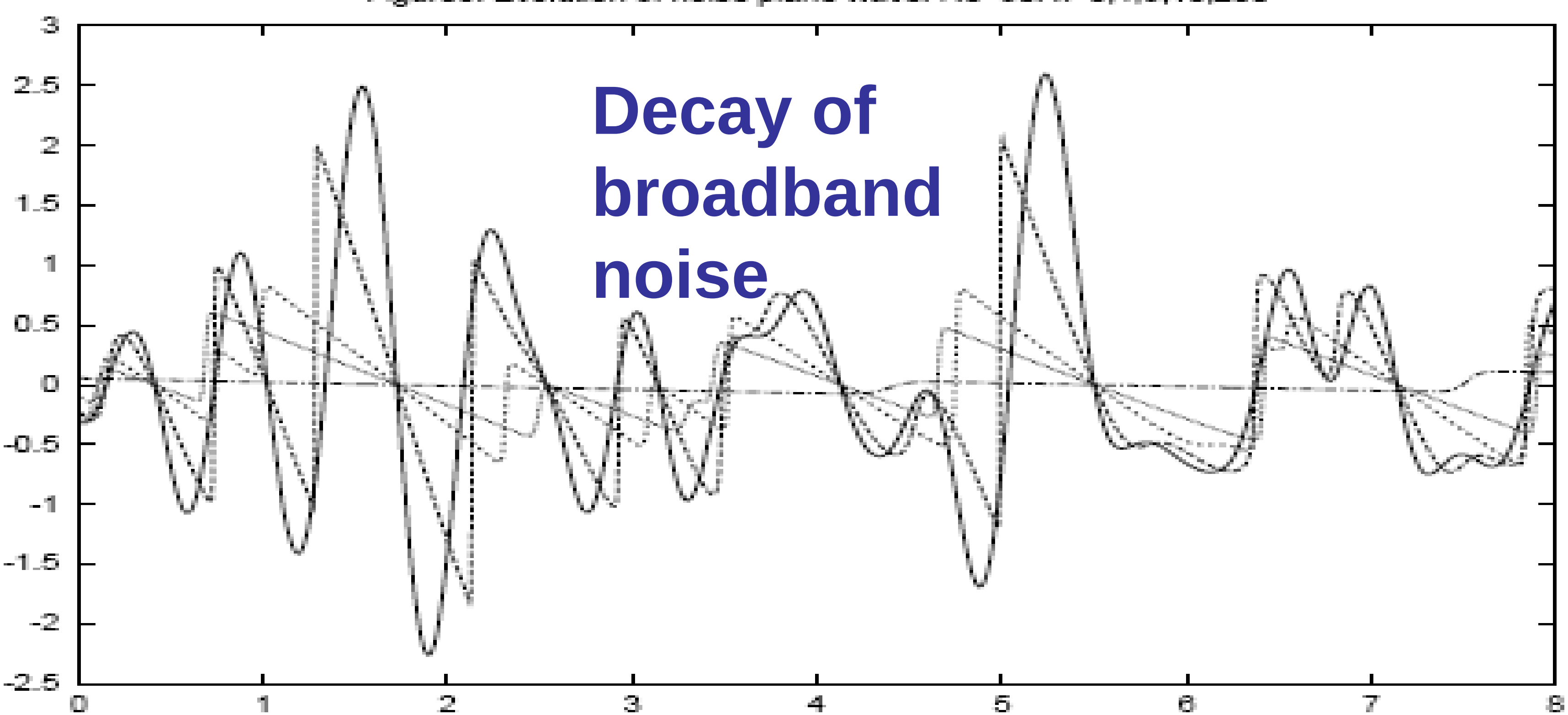




Section of spatio-temporal correlation function. Mixing of spectra leads to amplification of spatial and temporal correlation

Steady-state spectra of diffracting sound beam in the far field. Nonlinear effects increase with number of curve

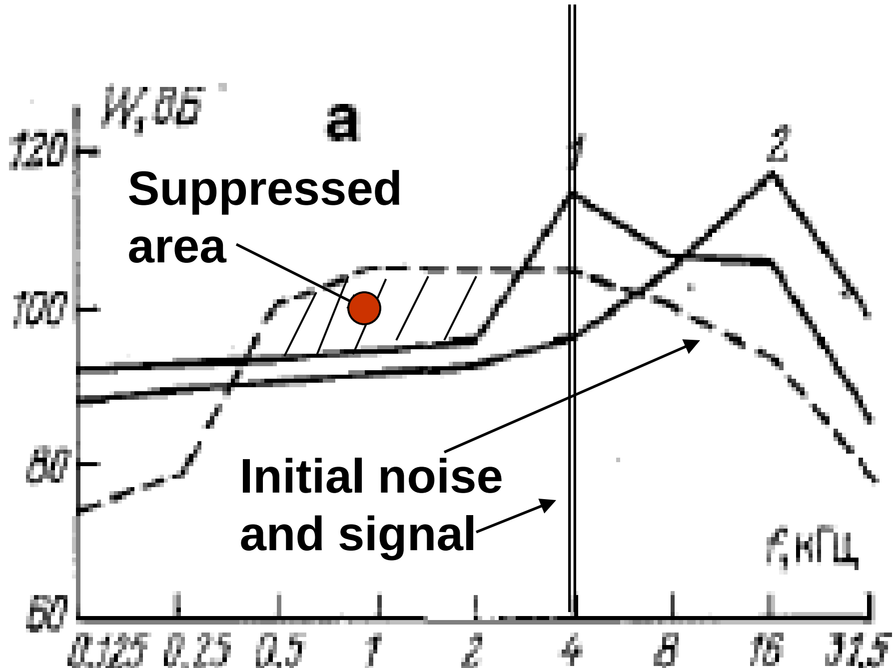


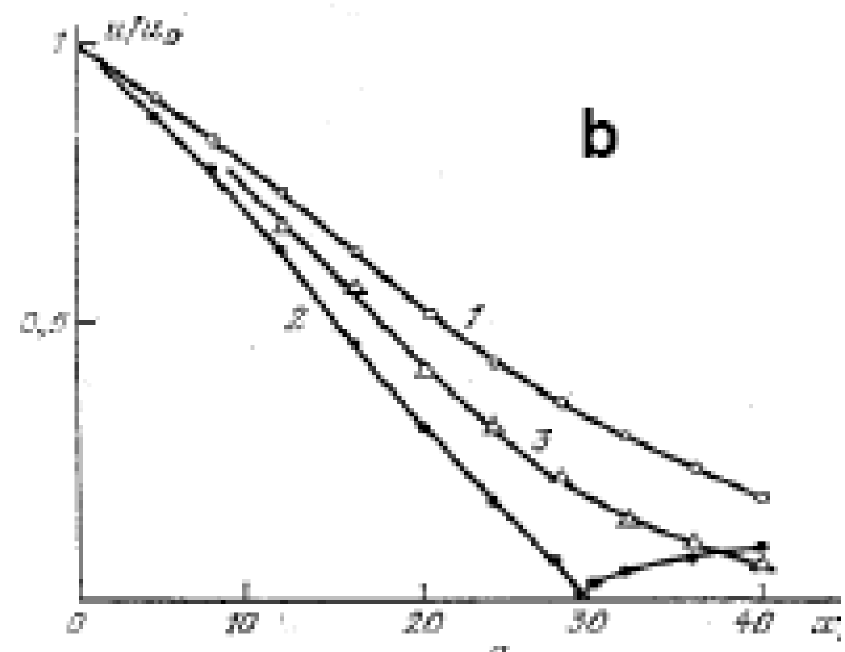


The multiple merging of discontinuities leads to a loss of information on the fine structure of the initial signal, and, at long distances, a self-similar spectrum is formed, whose evolution in time is determined by a single time scale $\tau(z)$.

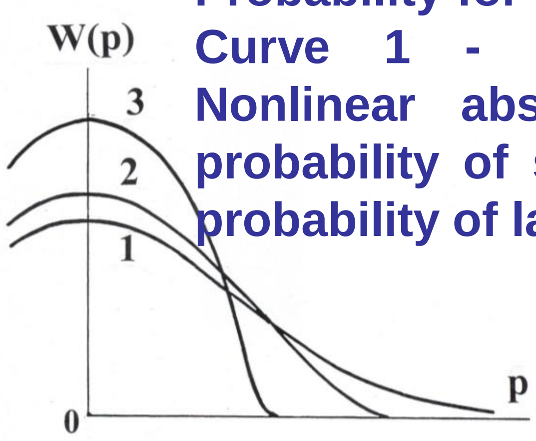
In the high-frequency and low-frequency regions, the spectrum has universal asymptotics $E(\omega, z) \sim \omega^{-2} z^{-3/2}$ and $E(\omega, z) \sim \omega^{2} z^{1/2}$ respectively.

It is possible to observe also the initial noise damping (dotted line in Fig.a) and additional nonlinear absorption of signal

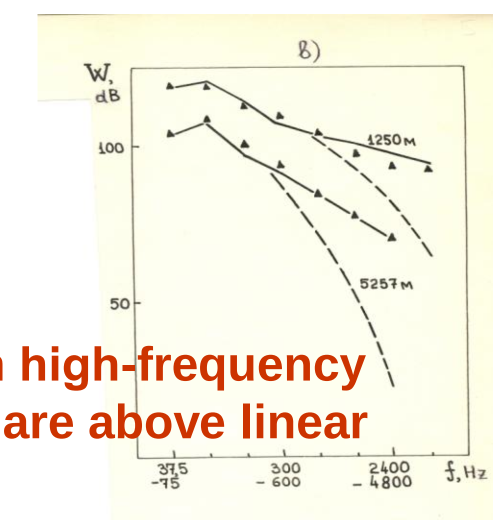




Experiments: suppression of low-frequency noise by high-frequency signal (a) and decay of tone signal in noise field (b)



Probability for nonlinear quasi-harmonic noise. Curve 1 - initial Gaussian distribution.. Nonlinear absorption of shocks increases probability of small pressures and decreases probability of large outbursts (2 ,3).



Noise spectrum of “Atlas-D”. In high-frequency region nonlinear (solid) curves are above linear (dashed) curves.

General approach to the nonlinear evolution of noise spectra

1. If initial spectrum $S_0(\Omega)$ of stationary noise is known, we can calculate the auxiliary correlation function $R_A(z,T)$

$$R_A(z,T) = \int_{-\infty}^{\infty} S_0(\Omega) \exp\left[-i\Omega T - 2Dz\Omega^2 \int_0^{\infty} K(s)\cos(\Omega s)\, ds \right] d\Omega$$

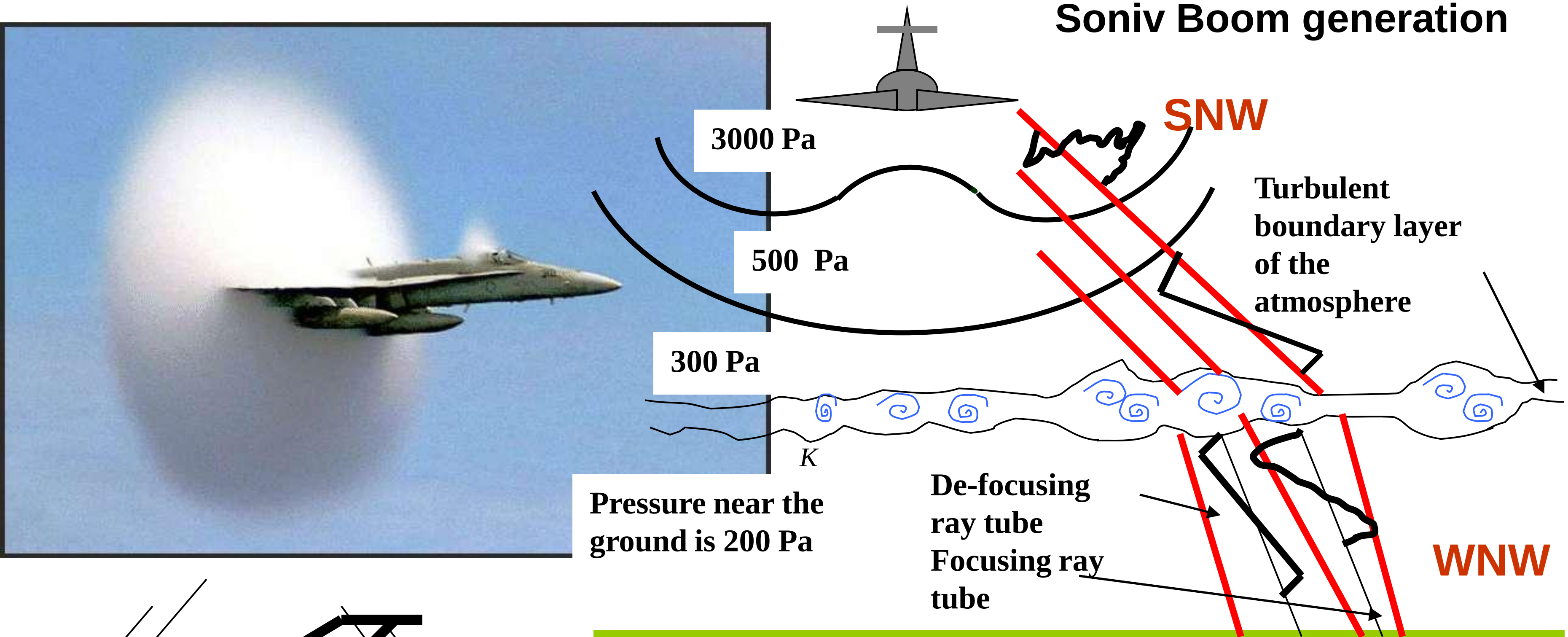
2. Now it is necessary to perform nonlinear integral transformation to calculate the correlation function of acoustic pressure at arbitrary distance traversed by the wave in nonlinear medium:

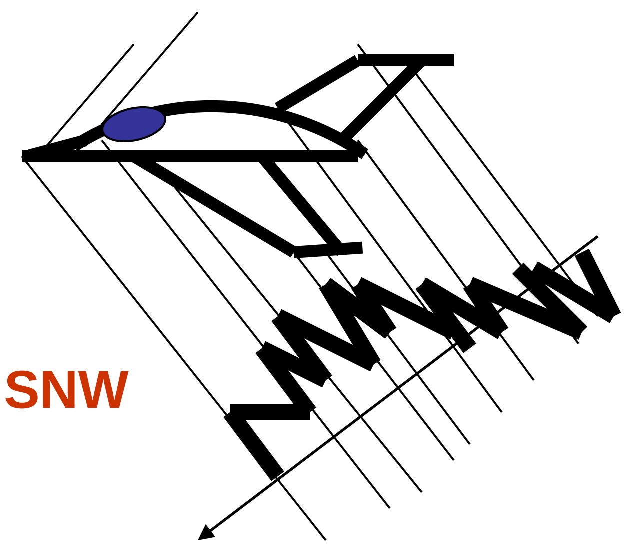
$$R(z,\theta) = -\frac{1}{2} \int_{-\infty}^{\infty} \Phi\left[\frac{T-\theta}{2z\sqrt{\sigma_A^2(z) - R_A(z,T)}} \right] \frac{\partial R_A(z,T)}{\partial T} dT, \quad \Phi \equiv erf$$

3. Performing Fourier transformation in accordance with Wiener-Khinchin theorem, we calculate spectrum for arbitrary distance: $S(z,\theta)$

4. Integral intensity of noise equals to: $\sigma^2(z) = R(z,0)$

3. Sonic booms in turbulent atmosphere



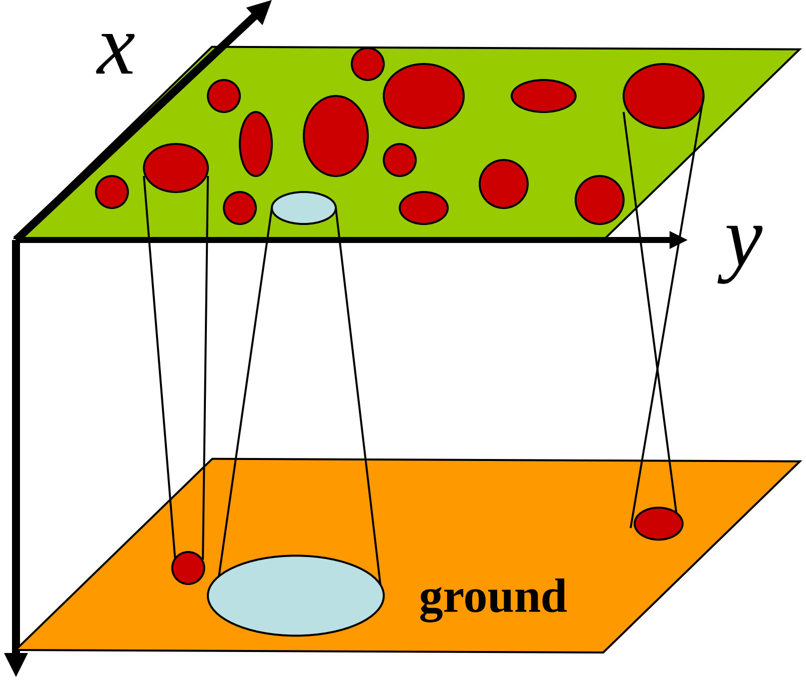


Relaxation of atmospheric gases must be taken into account

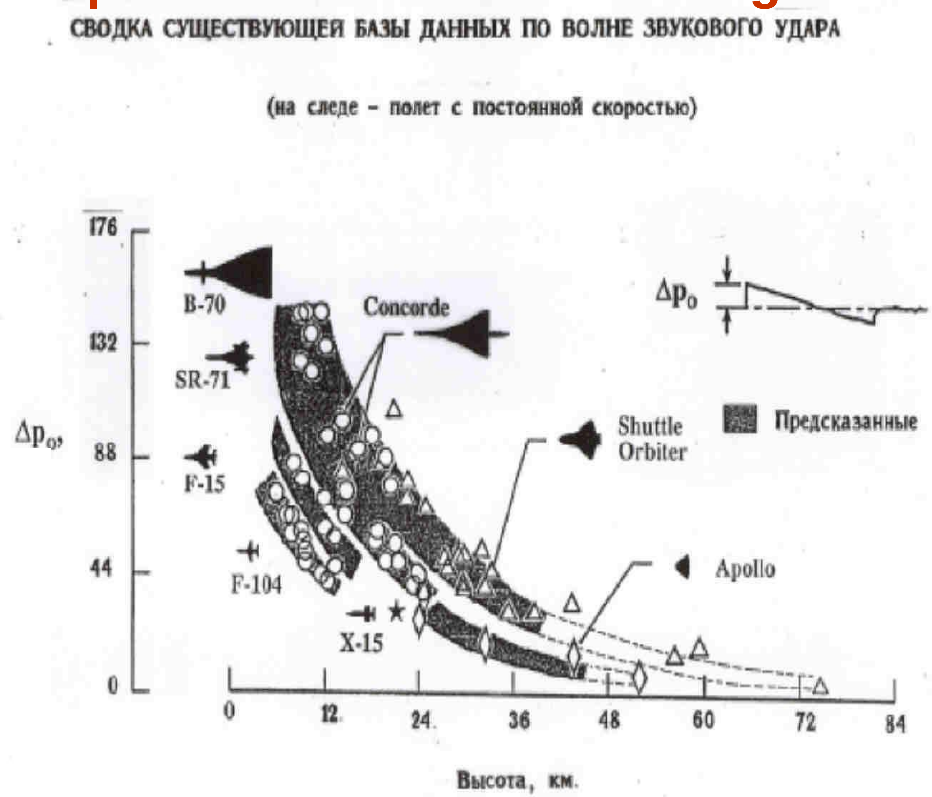
$$K(s)=\sum_{n=1}^{3} m_n \exp\left(-s/t_n\right)$$

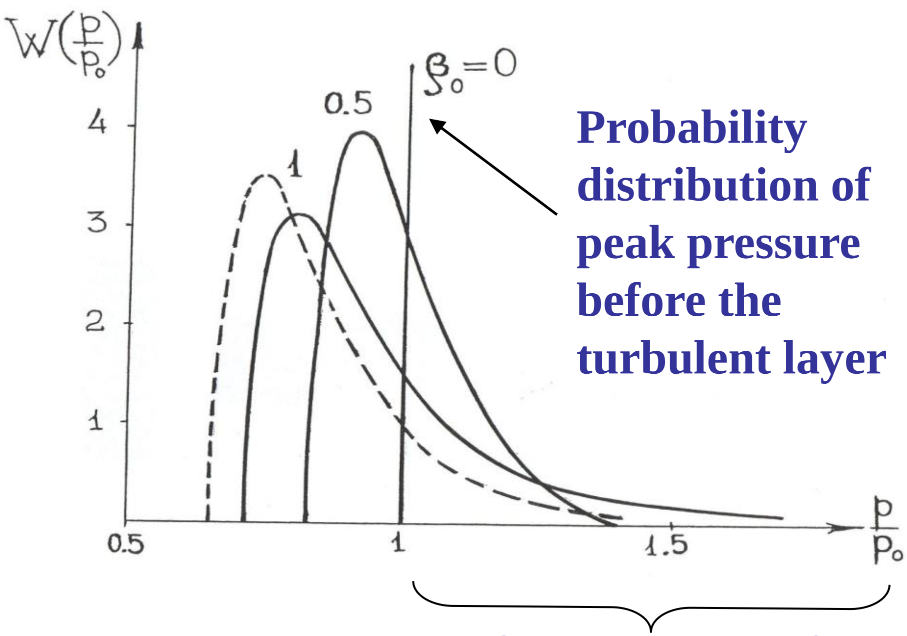
This kernel of IDE corresponds to relaxation of oxygen (n=1), nitrogen (n=2), carbon oxide (n=3)

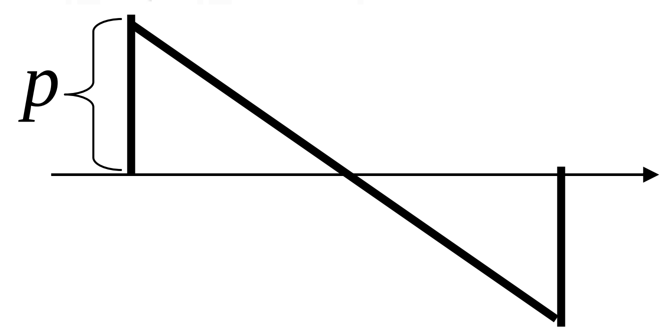
Probability distribution of peak pressure in the SB pulse



Experimental data on SB peak pressure measured at the ground



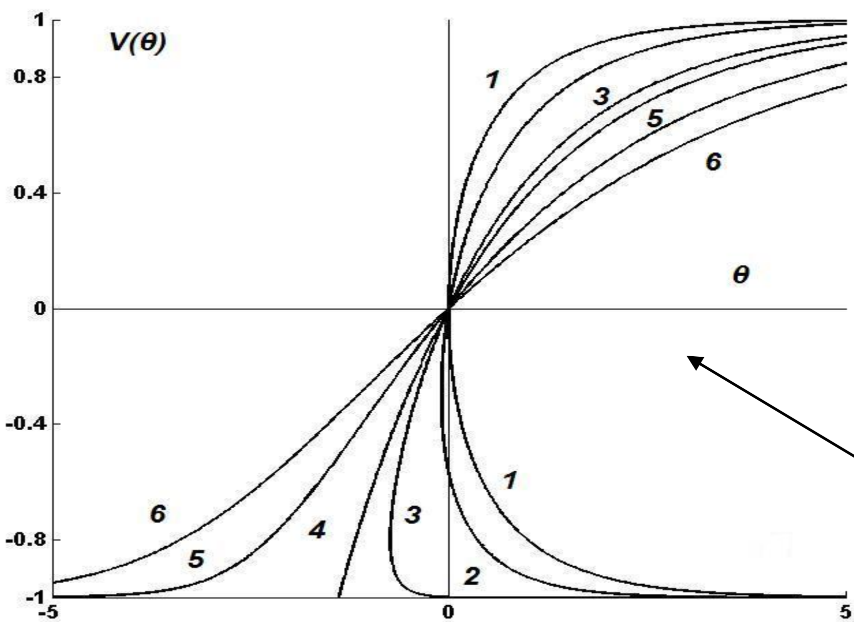




Probability of high strength fluctuation

However, main harmful impact on humans and technical equipment produces not high acoustic pressure, but rather high pressure gradient. It depends on the steepness of shock fronts. In turn, the shock width depends on molecular relaxation of atmospheric gases. Wave propagation in such media is governed by nonlinear IDE:

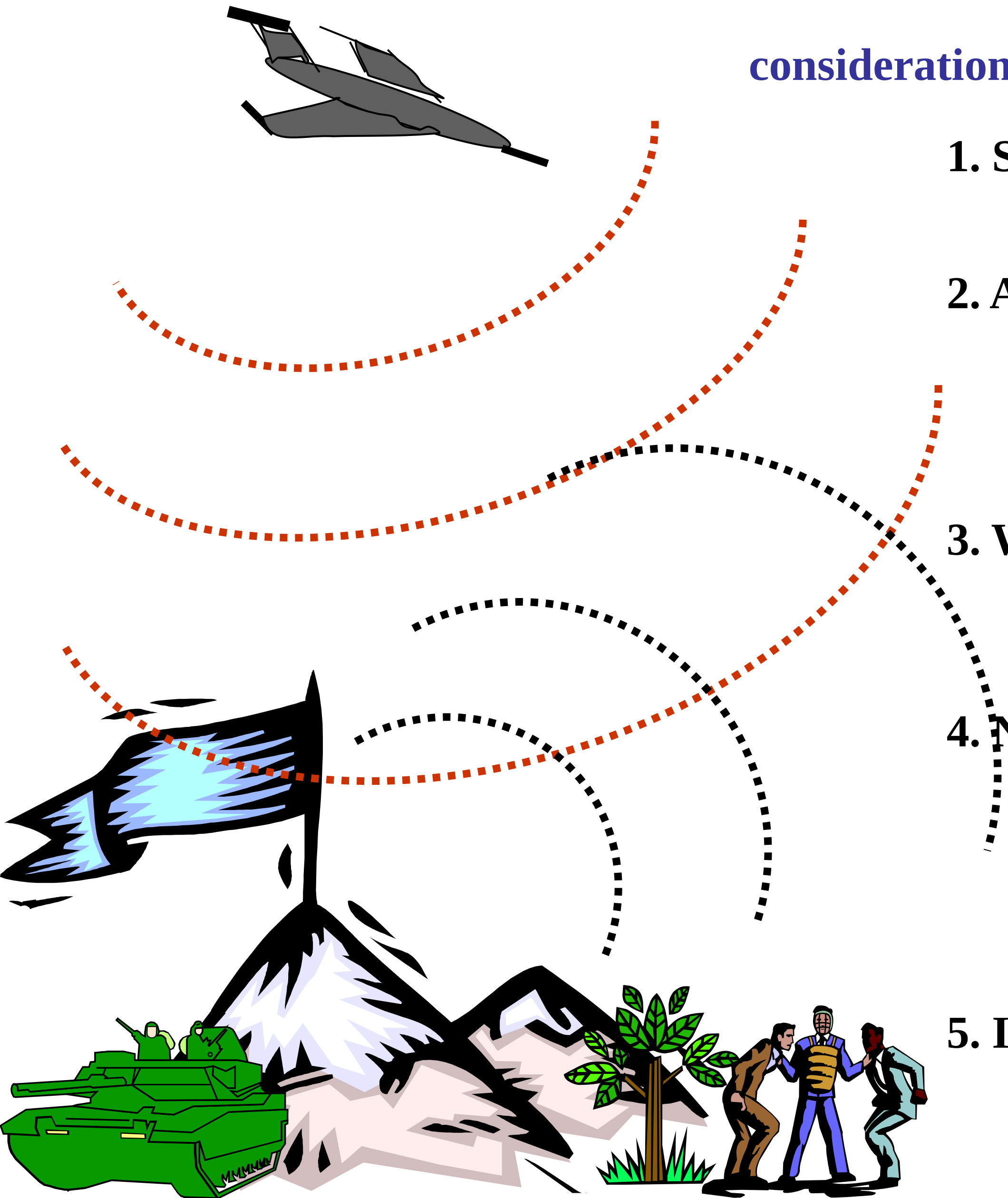
$$\frac{\partial}{\partial \tau}\left[\frac{\partial p}{\partial z}-\frac{\varepsilon}{c_0^3\rho_0}\,p\,\frac{\partial p}{\partial \tau}-\frac{m_0}{2c_0}\frac{\partial^2}{\partial \tau^2}\int_0^\infty K\left(\frac{\xi}{t_0}\right)p(\tau-\xi)d\xi\right]=\frac{c_0}{2}\Delta_\perp p$$



The form of kernel can be calculated on the base of models of molecular kinetics. The kernel also can be reconstructed using measured frequency dependencies of sound velocity and absorption.

Profiles of shock waves calculated for exponential kernel

Expert System for selection of optimum regime and route of SPA flight



consideration must be given to:

1. **SPA:** aerodynamics, speed, manoeuvring, route
2. **Atmosphere:** stratification, regular inhomogeneity, turbulence, humidity, wind, molecular composition
3. **Wave:** nonlinearity, diffraction, refraction, scattering, absorption, molecular relaxation
4. **Nature of the ground:** relief, acoustical properties of boundaries, response to pulse signal, penetration to the ocean and to the ground through the rough surface
5. **Impact on:** living beings (humans, marine and terrestrial animals), buildings and equipment

Penetration depth of 1 MHz - ultrasound in different biological tissues (intensity decreases «e» times)

Lungs	0.2 cm
Scull bones	0.7 cm
Skin	2.5 cm
Muscle,along fibers	6 cm
Brain	9 cm
Blood	40 cm
Blood plasma	140 cm
Water	35 m

Frequency dependence of absorption is $\sim f^{n}$, where index n varies from 2.1 (for skull bones), and 1.7 (testicle), to 1.1 (muscle of skeleton) and 0.6 (skin)

Power index n is a fractional number. Therefore waves in tissues cannot be described by differential equations. The adequate model for waves in tissues is IDE, where kernel K(s) is different for different media.

ISSN 1063-7710, Acoustical Physics, 2013, Vol. 59, No. 5, pp. 584–589. © Pleiades Publishing, Ltd., 2013.
Original Russian Text © O.V. Rudenko, S.N. Gurbatov, I.Yu. Demin, 2013, published in Akusticheskii Zhurnal, 2013, Vol. 59, No. 5, pp. 630–635.

Nonlinear Noise Waves in Soft Biological Tissues

O. V. Rudenko[a, b, c, d, e], S. N. Gurbatov[e], and I. Yu. Demin[e]

$$\frac{\partial p}{\partial x} - \frac{\varepsilon}{c^3\rho} p \frac{\partial p}{\partial \tau} - \frac{m}{2c}\frac{\partial p}{\partial \tau} - \frac{m}{2ct_0}\frac{\partial}{\partial \tau}\int_0^\infty K'\left(\frac{\xi}{t_0}\right) p(x, \tau - \xi) d\xi = 0.$$

$$E = R(z,0) = -\frac{1}{2}\int_{-\infty}^{\infty} \Phi\left[\frac{T}{2z\sqrt{\sigma_A^2 - R_A}}\right]\frac{\partial R_A}{\partial T} dT = 2a\int_1^\infty \Phi\left[Y\frac{\beta}{2\sqrt{T_C}}\sqrt{\frac{a}{(a-1)^3}}\right]\frac{dY}{Y^3}.$$

Absorption rate of wave energy is required for US therapy. Examples are hyperthermia, ablation, etc.

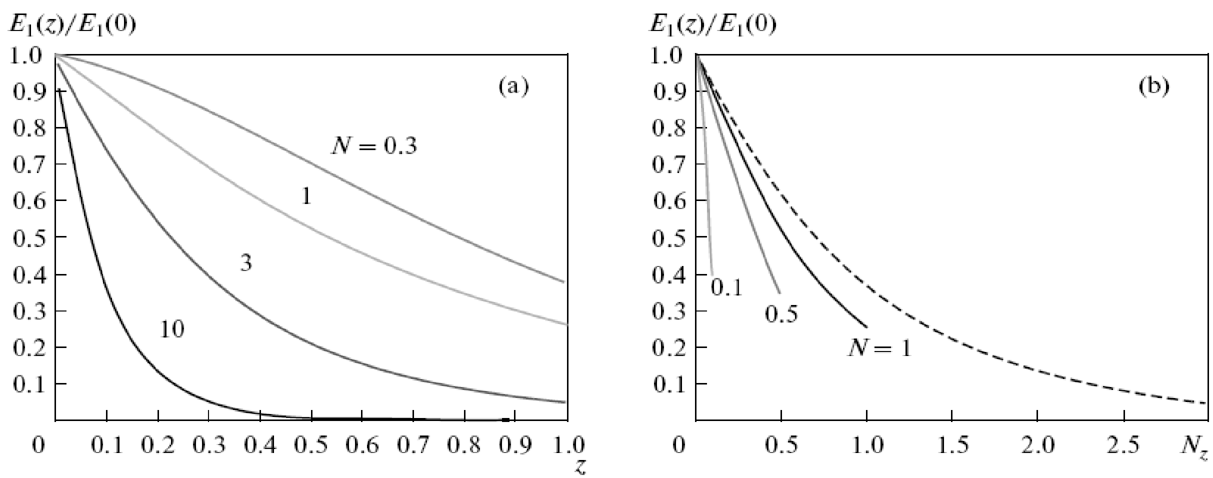


Fig. 1. Dependence of intensity of first noise harmonic on distance $z = x/x_{SH}$ in units of nonlinear lengths (a); on distance $Nz = x/x_D$ in units of dispersion-dissipation lengths (b) for different values of the ratio of characteristic lengths $N = x_{SH}/x_D$, depicted in the figure.

IOP PUBLISHING JOURNAL OF PHYSICS A: MATHEMATICAL AND THEORETICAL

J. Phys. A: Math. Theor. 44 (2011) 315201 (21pp) doi:10.1088/1751-8113/44/31/315201

Group analysis of evolutionary integro-differential equations describing nonlinear waves: the general model

Nail H Ibragimov[1], Sergey V Meleshko[2] and Oleg V Rudenko[3,4]

$$\frac{\partial}{\partial\tau}\left[\frac{\partial p}{\partial x}-\frac{\varepsilon}{c^3\rho}p\frac{\partial p}{\partial\tau}-W\right]=\frac{c}{2}\Delta_\perp p,$$

$$W=\frac{m}{2c}\frac{\partial}{\partial\tau}\int_{-\infty}^{\tau}K\left(\frac{\tau-\tau'}{t_0}\right)\frac{\partial p}{\partial\tau'}\,d\tau'$$
$$=\frac{m}{2c}\frac{\partial^2}{\partial\tau^2}\int_0^{\infty}K\left(\frac{\xi}{t_0}\right)p(\vec{r},\tau-\xi)\,d\xi.$$

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ELSEVIER

K is the kernel describing non equilibrium internal dynamics of given medium

Effect of resonant absorption in viscous and dry vibrating contact: Mathematical models and theory connected with slow dynamics and friction welding

R.K. Gazizov[a], N.H. Ibragimov[a,b,*], O.V. Rudenko[c,d]

ISSN 1063-7710, Acoustical Physics, 2012, Vol. 58, No. 3, pp. 269–276. © Pleiades Publishing, Ltd., 2012.
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NONLINEAR ACOUSTICS

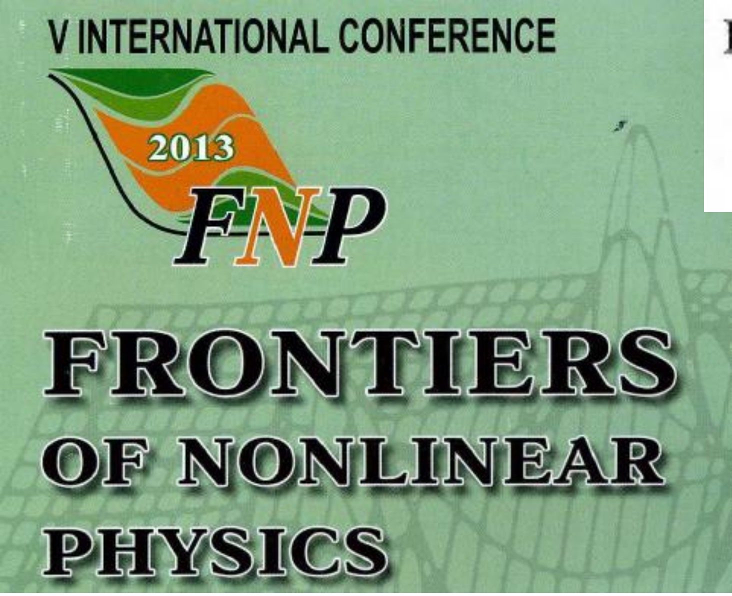
Nonlinear Acoustic Waves in Channels with Variable Cross Sections

V. F. Kovalev[a] and O. V. Rudenko[b]

Acknowledgments

We acknowledge a financial support of the Government of Russian Federation through Resolution No. 220, Agreements No. 11.G34.31.0042 at Ufa State Aviation Technical University and No. 11.G34.31.066 at N.I. Lobachevski Nizhni Novgorod State University.

For confluent kernels known Burgers, KdV, Rudenko-Robsman, Khokhlov-Zabolotskaya and Kadomtsev-Petviashvili models may be derived from IDE.



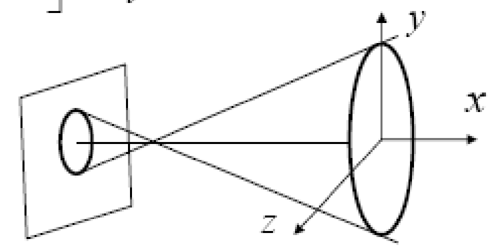
Integro-differential equations in nonlinear wave physics. Part 1. Dynamics

O.V. Rudenko

"General" evolution equation for nonlinear waves is

$$\frac{\partial}{\partial t}\left[\frac{\partial u}{\partial x}-u\frac{\partial u}{\partial t}-\frac{\partial^2}{\partial t^2}\int_0^\infty K(s)u(t-s)ds\right]=\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}=\Delta_\perp u \qquad (1)$$

Here t is the time, and x, y, z - Cartesian coordinates. The coordinate x coincides with the preferred orientation of the wave propagation. Other (transversal) coordinates are introduced in the cross-section of a beam.



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100 Top-Ranked Specialties in the Sciences and Social Sciences

MATHEMATICS, COMPUTER SCIENCE AND ENGINEERING

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	High-energy rechargeable lithium-air batteries	49	2,006	2010.8
2	* Boundary value problems of nonlinear fractional differential equations	47	1,172	2010.2
3	Chemical kinetic reaction mechanism for combustion of biodiesel fuels	49	1,555	2010.0
4	Nonlocal Timoshenko beam theory and carbon nanotubes	39	1,480	2009.8
5	Constrained total-variation image de-noising and restoration	49	2,741	2009.7
6	Graphene transistors	16	2,270	2009.7
7	Analyzing next-generation DNA sequencing data	6	2,025	2009.6
8	Heat transfer in nanofluids	40	1,928	2009.6
9	Calcium looping process for carbon dioxide capture	36	1,562	2009.6
10	Differential evolution algorithm and memetic computation	30	1,351	2009.6

An example of 1D equation is:

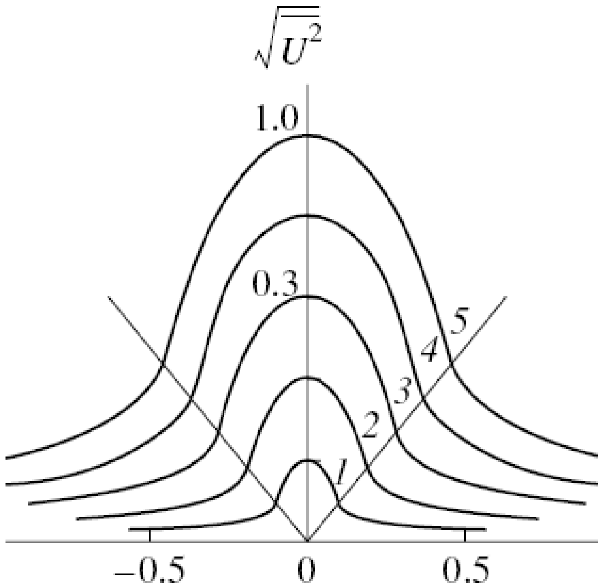
$$\frac{\partial u}{\partial x}-\frac{\varepsilon}{c^2}u\frac{\partial u}{\partial \tau}=\frac{b}{2c^3\rho}\frac{\partial^2 u}{\partial \tau^2}-g\frac{\partial}{\partial \tau}\int_0^\infty u(x,\tau-\xi)\frac{d\xi}{\sqrt{\xi}}$$

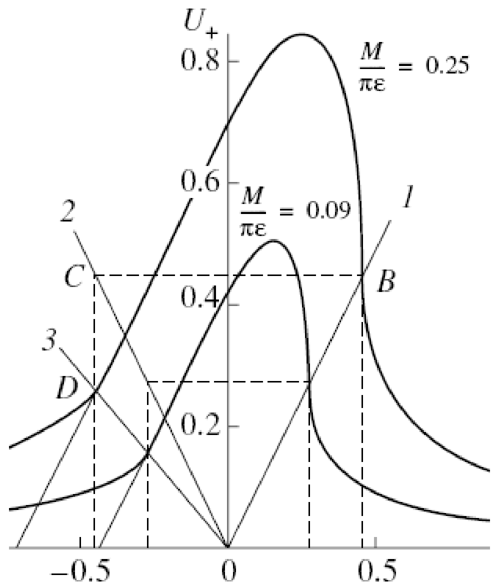
Fractional derivatives are defined in the Riemann-Liouville sense

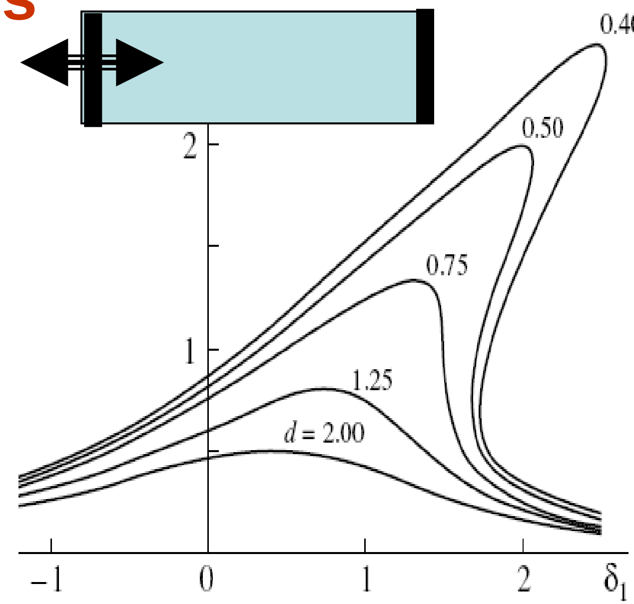
$$\left(D_{0^+}^\alpha u\right)=\frac{\partial^\alpha u}{\partial t^\alpha}=\frac{1}{\Gamma(n-\alpha)}\frac{\partial^n}{\partial t^n}\int_0^t\frac{u(s,x)ds}{(t-s)^{\alpha+1-n}} \qquad n-1<\alpha<n,\ n\in N$$

Interesting that studies of IDE with particular "fractional" kernels were most cited (in 2013) among all mathematical works. Statistical analysis was performed by "Thomson Reuters".

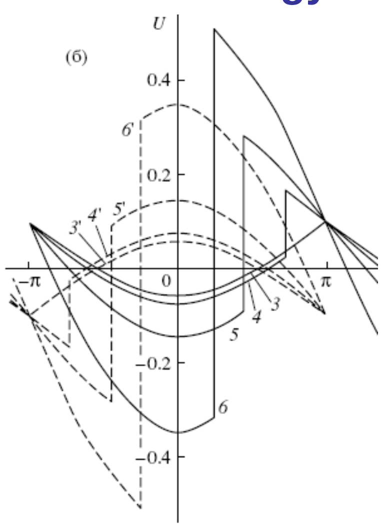
5. Standing waves in gas-filled resonators







Frequency response of quadratically nonlinear resonator determined as dependence of energy on frequ



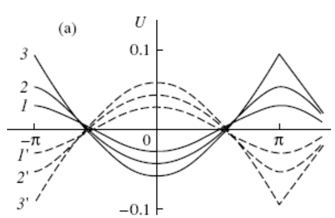
Frequency response determined as dependence of positive peak pressure on frequency

Frequency response of cubically nonlinear resonator

Linear Q-factor: $Q_{LIN} = \sqrt{\dfrac{c_0^2 \rho_0}{\pi\, b\, \omega}}$

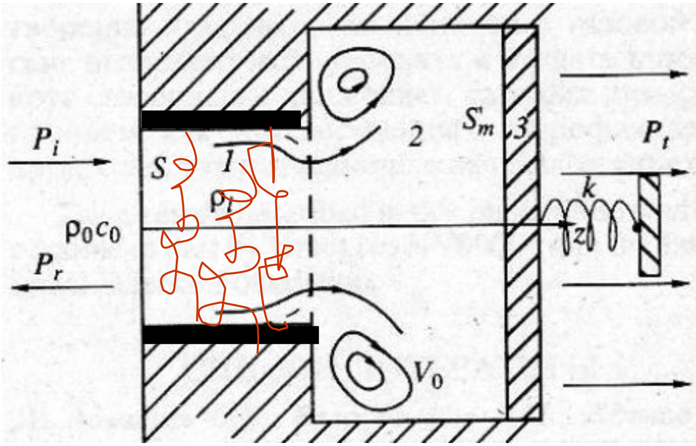
depends on effective viscosity b and frequency

Nonlinear Q-factor decreases with increase in pump amplitude P_0 $\quad Q_{NL} = \sqrt{\dfrac{c_0^2 \rho_0}{\pi\, \varepsilon\, P_0}}$



$$\frac{Q_{LIN}}{Q_{NL}} = \sqrt{\frac{\varepsilon P_0}{b\omega}} = \sqrt{\mathrm{Re}_{AC}} >> 1$$

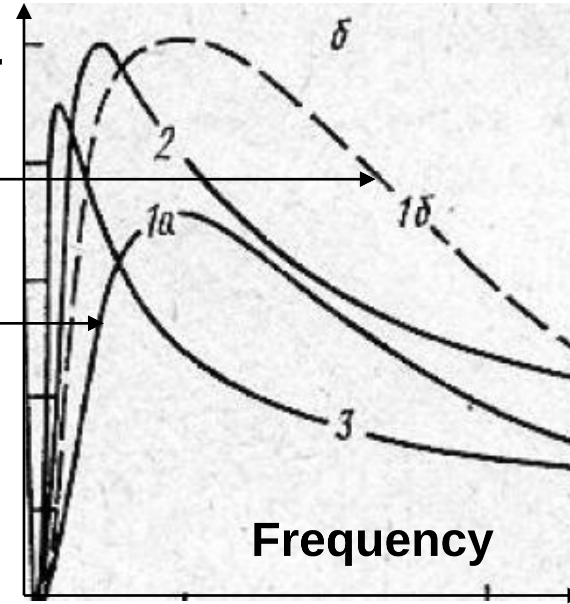
6. Nonlinear Helmholtz resonator for high-intensity sound absorber



Absorption coefficient 1

Nonlinear

Linear



Frequency

Nonlinearity can detune the resonance, if linear regime is tuned. In opposite, nonlinearity can amplify absorption due to acoustic impedance matching

$$\frac{d^2U}{dt^2} + \omega_0^2 U + \left(\nu a_2 n + \frac{c_0\rho_0}{\rho_ж L} \right)\frac{dU}{dt} + \frac{1}{a_1}\sqrt{\frac{\nu}{\pi}}\,\frac{d}{dt}\int\limits_{-\infty}^{t}\frac{dU}{dt'}\,\frac{dt'}{\sqrt{t-t'}} +$$

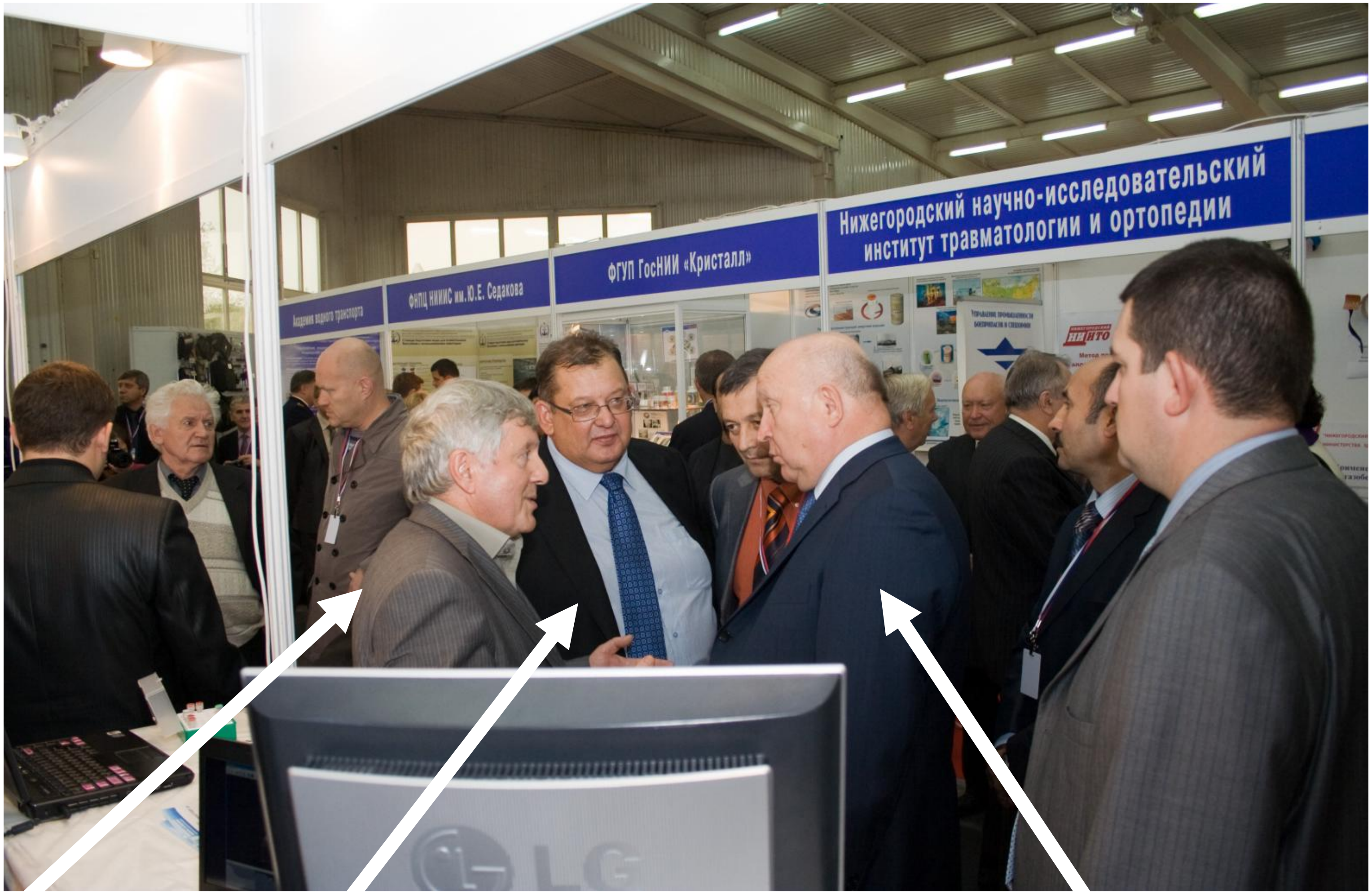
$$+ (\gamma_1 U + \gamma_2 U^2)\frac{dU}{dt} = \frac{2}{\rho_ж L}\,\dot{p}_п(t).$$

$$p_{ак}(x,t) = p_п(t - x/c_0) + p_{отр}(t + x/c_0),$$

$$u(x,t) = \frac{1}{c_0\rho_0}\left[p_п\left(t - \frac{x}{c_0}\right) - p_{отр}\left(t + \frac{x}{c_0}\right)\right]$$

It is possible to control the absorptance and frequency band of resonator electronically or mechanically

One can meet nonlinear phenomena in many areas of natural sciences and engineering



Rudenko and Gurbatov demonstrate to the Governor Shantsev their new medical devices during the exibition of innovations

General information about the journal "Acoustical Physics"

Acoustical Physics (*Akusticheskii zhurnal*), founded in 1955, is the only Russian academic journal in the field of acoustics.

Impact-Factor: 0.68 (2010), 0.7 (2011), 0.45 (2012), 0.55 (2013)

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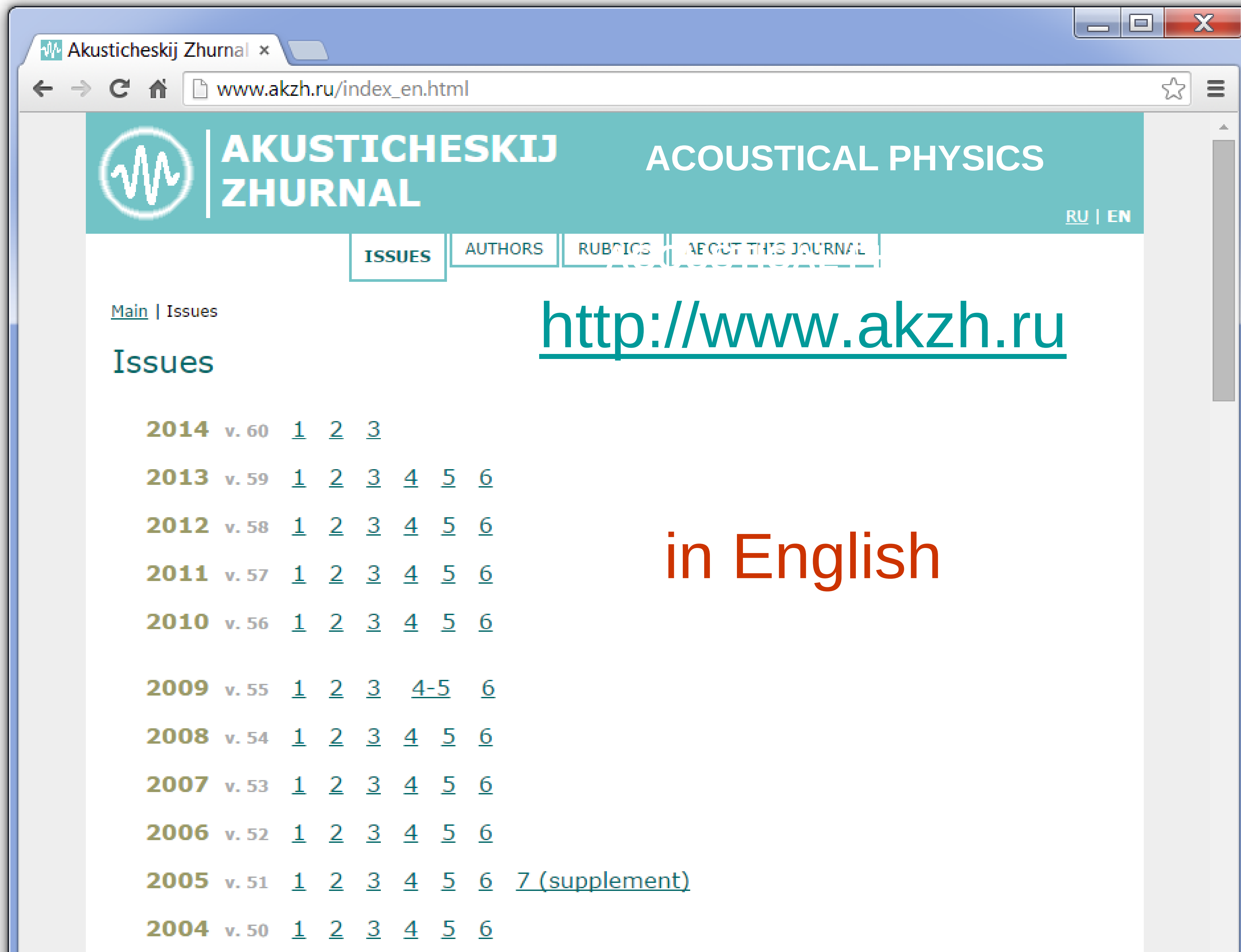

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- 04.02 Лучевая акустика
- 04.03 Отражение, дифракция и рефракция волн
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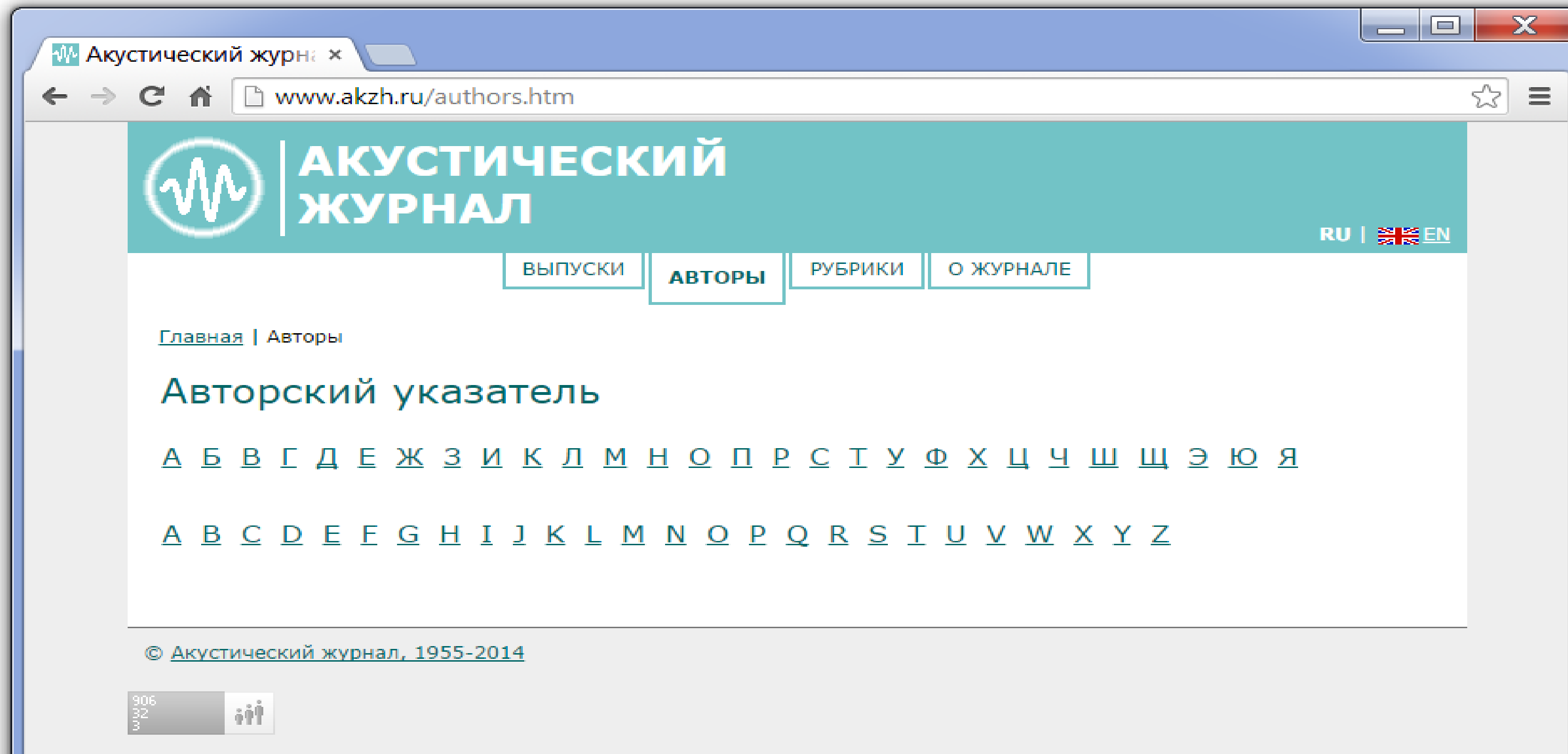

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Гордиенко В.А., Гордиенко Т.В., Краснописцев Н.В., Некрасов В.Н. «Векторно-фазовые методы и создание перспективных акустических систем нового поколения» *Вестник Московского университета. Серия 3: Физика. Астрономия*, № 2, с. 3-21 (2014)

Обсуждаются результаты теоретических и экспериментальных исследований, цель которых – обоснование потенциальных возможностей векторно-фазовых методов при решении различных прикладных задач гидроакустики. Эти исследования во многом способствовали активному внедрению векторно-фазовых методов в практику гидроакустических измерений. Преимущества векторно-фазовых методов, особенно в гидроакустике, проявляются прежде всего при существенном ограничении области пространства для размещения их в среде. В случае размещения одиночного комбинированного приемного модуля (КПМ) имеет место качественный скачок, который состоит в появлении нового "качества" у точечной приемной системы – возможности определения местоположения источника звука. Другая особенность использования КПМ – возможность применения принципиально новых (по отношению к системам на базе гидрофонов) алгоритмов обработки информации, основанных на прямом измерении потока акустической энергии (мощности), т. е. выделении той ее части, которая обусловлена анизотропией поля или наличием в среде сосредоточенных источников.

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Шахпаронов В.М. «Методики решения системы нелинейных уравнений колебаний для определения гравитационной постоянной» *Вестник Московского университета. Серия 3: Физика. Астрономия*, № 2, с. 60-66 (2014)

Рассмотрены методики решения системы нелинейных уравнений колебаний. Показана перспектива расширения функциональных возможностей имеющихся методик для определения гравитационной постоянной *G* при несферичной форме взаимодействующих тел. Проанализирована работа, описанная в ДАН СССР, т. 245, №3 за 1979 г. Зависимость значений *G* от позиций притягивающих масс можно объяснить наличием парамагнитного эффекта. Его имитация точечной массой с определением ее величины и положения привела к получению стандартного значения *G*.

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Гордиенко В.А., Гордиенко Т.В., Задорожный С.С., Исайчев С.А., Учаев А.В., Амосов М.А. «Некоторые особенности восприятия слуховыми нейронами низкочастотных сигналов» *Вестник Московского университета. Серия 3: Физика. Астрономия*, № 2, с. 88-97 (2014)

Рассмотрены некоторые особенности восприятия слуховыми нейронами человека инфразвуковых колебаний, генерируемых изменением частоты и громкости звукослышимого диапазона. Показано, что слуховые нейроны реагируют на громкостную огибающую, выделяя соответствующие инфразвуковые частоты для последующей их обработки. Данный механизм возможен, если ухо работает в нелинейном режиме, производя детектирование с последующим временным усреднением не менее 40–50 мс. При совпадении частоты звукового кода с каким-либо ритмом головного мозга может возникнуть резонанс, увеличивающий амплитуду соответствующего ритма.

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