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Wave-like processes in quasi-one-dimensional mesoscopic structures

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Annotation.

This work is based on the topological properties of the solution one-dimensional unsteady gas flow system with constant speed sonic. The paper presents the principle of constructing a mesoscopic analogy-computing device that implements addition and multiplication operations. The fie effect, which is modeled by these operations, is observed in linear polymolecular structures and represents the flow of electron gas (quantum current). Such structures can be created artificially, but they have analogues in biological objects, for example, DNA and mtDNA. In support of these facts, the result of processing data from an experiment on studying sunflower seeds using impedance spectroscopy is interpreted.

Keywords: one-dimensional unsteady gas flow system, quantum electron gas current, mesoscopic poly-molecular structure, analogy-calculation devise, mtDNA and terahertz radiation

Theoretical introduction.

First, consider the solution of a one-dimensional system of equations for unsteady gas flow (equations of motion and continuity equations written in Euler form):

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+\frac{a^2}{\rho}\frac{\partial \rho}{\partial x}=0 \quad ; \quad \frac{\partial \rho}{\partial t}+V\frac{\partial \rho}{\partial x}+\rho\frac{\partial V}{\partial x}=0 \tag{1}$$

It's a problem for velocity $V(x,t)$ and density $\rho(x,t)$, $U=a\ln\frac{\rho}{\rho_0}$ with constant speed sonic « a » the physical justification for this assumption will be given below (in applications):

$$\frac{\partial}{\partial t}(V\pm U)+(V\pm a)\frac{\partial}{\partial x}(V\pm U)=0 \tag{2}$$

Solution represented as a sum of two parts $V=v+V_0$; $U=u+U_0$ one of which is a solution to a linear problem that satisfies the boundary conditions of the initial problem (1-2):

$$\frac{\partial}{\partial t}(V_0\pm U_0)\pm a\frac{\partial}{\partial x}(V_0\pm U_0)=0$$

$$V_0=\frac{1}{2}\left(H_1(x-at)+H_2(x+at)\right) \quad ; \quad U_0=\frac{1}{2}\left(H_1(x-at)-H_2(x+at)\right) \tag{3}$$

The other part satisfies the following equations (in this case, the boundary conditions may be zero):

$$\frac{\partial(v\pm u)}{\partial t}+(v+V_0\pm a)\frac{\partial(v\pm u)}{\partial x}+(v+V_0)\frac{\partial}{\partial x}(V_0\pm U_0)=0 \tag{4}$$

Solution (4) determinate by introduction $h_1=v+u$; $h_2=v-u$ these parts are the solution of the equations:

$$\frac{\partial h_1}{\partial t}+(V+a)\frac{\partial h_1}{\partial x}+V\frac{\partial H_1}{\partial x}=0 \quad ; \quad \frac{\partial h_2}{\partial t}+(V-a)\frac{\partial h_2}{\partial x}+V\frac{\partial H_2}{\partial x}=0 \tag{5}$$

Secondly, we denote $y=at$; $\alpha=\frac{V}{a}$ and the solution of equations (5) is represented by two functions $h_1(x)$; $h_2(y)$, each with one variable (the details leading to this are set out in [1], and in those works to which there are references):

$$h_1' = -\frac{\alpha}{\alpha+1} H_1' = F_1(x); \quad h_2' = -\alpha H_2' = F_2(y) \tag{6}$$

Thirdly, the solution of equations (5) depends on two functions $F_1(x)$ and $F_2(y)$, which are found as solution of the functional equation, which is obtained from (6) by excluding of α:

$$\frac{H_2'(x+y)}{F_2(y)} - \frac{H_1'(x-y)}{F_1(x)} = 1 \tag{7}$$

The solution to this functional equation can be carried out according to the following scheme: we denote $\varphi_1 = \frac{1}{F_1}, \varphi_2 = \frac{1}{F_2}$ and differentiate with respect to $\frac{\partial}{\partial x}$, and then with respect to $\frac{\partial}{\partial y}$ the equation $\varphi_2(y) H_2'(x+y) - \varphi_1(x) H_1'(x-y) = 1$, obtaining the system accordingly:

$$\varphi_1' H_1' + \varphi_1 H_1'' - \varphi_2 H_2'' = 0 \quad ; \quad -\varphi_1 H_1'' - \varphi_2' H_2' - \varphi_2 H_2'' = 0$$

Let us add and subtract these equations, obtaining, respectively:

$$\varphi_1' H_1' - \varphi_2' H_2' = 2\varphi_2 H_2'' \quad ; \quad \varphi_1' H_1' + \varphi_2' H_2' = -2\varphi_1 H_1''$$

Let us express the derivatives from here

$$\begin{pmatrix} \varphi_1' \\ \varphi_2' \end{pmatrix} = \frac{1}{H_1' H_2'} \begin{pmatrix} H_2' & H_2' \\ -H_1' & H_1' \end{pmatrix} \begin{pmatrix} \varphi_2 H_2'' \\ -\varphi_1 H_1'' \end{pmatrix},$$

obtaining linear differential equations for the functions $\varphi_1(x), \varphi_2(y)$:

$$\varphi_1' + \varphi_1 \frac{H_1''}{H_1'} = \varphi_2 \frac{H_2''}{H_1'} \quad ; \quad \varphi_2' + \varphi_2 \frac{H_2''}{H_2'} = -\varphi_1 \frac{H_1''}{H_2'}$$

It solved by the method of variation of constant, while in the first the parameter by which differentiation and integration is not performed is considered "y", and in the second "x":

$$\varphi_1 = \exp\left(-\int \frac{H_1''}{H_1'} dx \right) \left(C_1 + \int \varphi_2 \frac{H_2''}{H_1'} \exp\left(\int \frac{H_1''}{H_1'} dx \right) dx \right)$$

$$\varphi_2 = \exp\left(-\int \frac{H_2''}{H_2'} dy \right) \left(C_2 - \int \varphi_1 \frac{H_1''}{H_2'} \exp\left(\int \frac{H_2''}{H_2'} dy \right) dy \right)$$

In the first equation, the function $\varphi_2(y)$: comes out from the integral over "x", and in the second – the function $\varphi_1(x)$ – from under the integral over "y".

$$\varphi_1(x)\left(H_1'(x-y)+F(y)\right)-\varphi_2(y)\left(H_2'(x+y)+f(y)\int\frac{H_2''(x+y)}{H_1'(x-y)}dx\right)=C_1 \tag{8}$$

$$\varphi_2(y)\left(H_2'(x+y)+G(x)\right)+\varphi_1(x)\left(H_1'(x-y)+g(x)\int\frac{H_1''(x-y)}{H_2'(x+y)}dy\right)=C_2 \tag{9}$$

In addition to integration constants C_1, C_2, the functions $F(y), f(y), G(x), g(x)$ also appear that specify the arbitrariness of the solution to equation (7).

Imposing the condition $\varphi_1(x)H_1'(x-y)-\varphi_2(y)H_2'(x+y)=C_1$ is equivalent to equation (7) taking into account the choice of constants $C=C_2=-C_1$ and scaling of functions F_1C, F_2C (without loss of generality we can set $C=1$).

In this case, equation (8) takes the form:

$$\varphi_1(x)F(y)=\varphi_2(y)f(y)\int\frac{H_2''(x+y)}{H_1'(x-y)}dx$$

Hence, if we introduce the notation of invariants $I_y(x);\ I_x(y)$, that is

$$\frac{\partial I_y(x)}{\partial y}=0;\ \frac{\partial I_x(y)}{\partial x}=0:$$

$$I_y(x)=f(y)\int\frac{H_2''(x+y)}{H_1'(x-y)}dx\ ;\ I_x(y)=g(x)\int\frac{H_1''(x-y)}{H_2'(x+y)}dy \tag{10}$$

$F_1(x)=\dfrac{F(y)F_2(y)}{I_y(x)}=\dfrac{1}{I_y(x)}$; $F_2(y)=\dfrac{1}{F(y)}$, hence from equation (9)

$$\frac{H_2'(x+y)+G(x)}{F_2(y)}+I_y(x)\left(H_1'(x-y)+I_x(y)\right)=1$$

can be found:

$$F_2(y)=\frac{H_2'(x+y)+G(x)}{1-I_y(x)\left(H_1'(x-y)+I_x(y)\right)}=F_1(x)\frac{H_2'(x+y)+G(x)}{F_1(x)-H_1'(x-y)-I_x(y)}$$

Arbitrariness remains in the choice of three functions $f(y), g(x), G(x)$ is to ensure the invariance of quantities $I_y(x), I_x(y), F_2(y)$.

Equation (7) is invariant (preserved) under the following simultaneous substitutions $\leftrightarrow$: $x \leftrightarrow y; f \leftrightarrow g; H_2'(z) \leftrightarrow -H_1'(-z); I_y(x) \leftrightarrow I_x(y); F_1(x) \leftrightarrow F_2(y)$, therefore, by a suitable choice of function $G(x)$, the equalities $F_1(x) = \frac{1}{I_y(x)}; F_2(y) = \frac{1}{I_x(y)}$ can be achieved.

Example of simple one of invariant (but not solutions to equation (7), that is, the function f is specified and not found):

$$f = 1; \quad H_1(x-y) = -e^{-(x-y)}; \quad H_2(x+y) = e^{x+y}$$

$$I_y(x) = \int \frac{H_2''(x+y)}{H_1'(x-y)} dx = \int \frac{e^{x+y}}{e^{y-x}} dx = \int e^{2x} dx = \frac{1}{2} e^{2x}$$

The presence of these invariants is a consequence of the fact that the dynamic system (6) is obtained as result of transforming problem (1-2) to an integrable system of the type of Hamilton equations (under the conditions of implementing canonical transformations to variables of the action-angle type).

For periodical case $H_{1,2}(x) = H_{1,2}(x+L)$ the scheme for searching for invariants (10) can be as follows:

The change $z = 2y\frac{x}{L}$ is lead to the $H_{1,2}\left(z\frac{L}{2y}\right) = H_{1,2}\left((z+2y)\frac{L}{2y}\right)$ or same: $H_{1,2}\left((z-y)\frac{L}{2y}\right) = H_{1,2}\left((z+y)\frac{L}{2y}\right)$

Then two ($\pm$) invariants

$$I_y^{\pm}(x) = f(y)\int \frac{H_2''(x+y)}{H_1'(x-y)} dx = f(y)\frac{L}{2y}\int \frac{H_2''\left((z \pm y)\frac{L}{2y}\right)}{H_1'\left((z \pm y)\frac{L}{2y}\right)} dz$$ from it's follow $f(y) = \frac{2y}{L}$,

is similarly searched for $I_x^{\pm}(y)$ by symmetry:

$$x \leftrightarrow y; f \leftrightarrow g; H_2'(z) \leftrightarrow -H_1'(-z); I_y(x) \leftrightarrow I_x(y); F_1(x) \leftrightarrow F_2(y)$$

This symmetry preserves only the scheme for finding invariants, but does not preserve the solution to problem (1-2), but this solution itself has time reversal symmetry:

$y \leftrightarrow -y;\ H_1 \leftrightarrow H_2$

Such a solution to the nonlinear problem (4) allows us to represent its topological structure, namely, let's denote $(s_1 = x,\ s_2 = y)$ then:

$$h_1 = \int_{s_1^0}^{s_1} F_1(s_1)ds_1 \ ;\ h_2 = \int_{s_2^0}^{s_2} F_2(s_2)ds_2$$

i.e. in 4D-space (h_1, h_2, s_1, s_2) , the manifold of the solution to problem (1-2) – phase manifold – is the 2D-intersection of the components of two orthogonal 3D-cylinders each of which is parallel with the planes (h_1, s_1) and (h_2, s_2)).

If $\alpha << 1$ then difference between solutions of problems (1-2) and (3) have a same order « α » according (6). Provided that the solution is periodic in the spatial coordinate (in a closed "ring" pipeline), the solution is also periodic in time; accordingly, the phase manifold is mapped to the 2D-torus in four-dimensional space (an invariant torus according to Liouville's theorem). In [1] it is proven that the nontrivial solution to problem (1-2) becomes generalized – weak or strong jumps are inevitable.

Order estimation of the physical quantities.

Analogue of the sound speed in an electron gas (inside nanowire), according to the estimate made in [2], is a value $a = \delta\sqrt{\frac{e\,\rho_e}{m_e\varepsilon_0}}$ that is considered constant. Electrons density in the nanowire $\rho_e = 10^8 \frac{Q}{m^3}$ (averaged); elementary charge $e \approx 1.60202 \cdot 10^{-19} Q$; electron mass $m_e \approx 9.1083 \cdot 10^{-31} kg$; electrical constant $\varepsilon_0 \approx 8.854304 \cdot 10^{-12} \frac{Q^2 \cdot s^2}{kg \cdot m^3}$ (also called the dielectric constant of vacuum); radius of the nanowire $\delta = 10^{-10} m$ (taken in order of magnitude equal to the average intra-atomic distance), here is an $a \approx 1.41 \cdot 10^5 \frac{m}{s}$. The speed of movement of charges in a quantum current is of the same order as in ordinary electrical wires $V \approx 10^{-3} \frac{m}{s}$

that is the order of magnitude of $\alpha \approx 10^{-8} << 1$ and the same is the order of magnitude of the difference between the solutions of linear (3) and nonlinear problems (1-2).

Conservation law and generalized solutions.

Next, we consider the quantity E, which can be perceived as the "mass-specific total energy of the gas" in the area between points with fixed coordinates x_1 and x_2 :

$$E = \int_{x_1}^{x_2} \left(\frac{V^2}{2} - a^2 \ln \frac{\rho}{\rho_0} \right) dx$$

The derivative of it with respect to time due to equations (1) will be as follows:

$$\frac{dE}{dt} = \int_{x_1}^{x_2} \left(V \frac{\partial V}{\partial t} - \frac{a^2}{\rho} \frac{\partial \rho}{\partial t} \right) dx =$$

$$= \int_{x_1}^{x_2} \left(-V \left(V \frac{\partial V}{\partial x} + \frac{a^2}{\rho} \frac{\partial \rho}{\partial x} \right) + \frac{a^2}{\rho} \left(V \frac{\partial \rho}{\partial x} + \rho \frac{\partial V}{\partial x} \right) \right) dx =$$

$$= \int_{x_1}^{x_2} \left(-V^2 \frac{\partial V}{\partial x} + a^2 \frac{\partial V}{\partial x} \right) dx = \left(a^2 V - \frac{V^3}{3} \right) \Bigg|_{x_1}^{x_2}$$

We obtain equation (10), in [4] it is called the "equation of hemodynamic energy balance" by analogy with the change in density during pulsation of the diameter of a blood vessel $\frac{D}{D_0} = \sqrt{\frac{\rho}{\rho_0}}$ and taking into account hydrostatics $E = \int_{x_1}^{x_2} \left(\frac{V^2}{2} - 2a^2 \ln \frac{D}{D_0} + gh \right) dx$. Here is the g – acceleration of gravity; $h(x)$ – dependence of the height of the vessel section on the longitudinal coordinate:

$$\frac{d}{dt} \int_{x_1}^{x_2} \left(\frac{V^2}{2} - a^2 \ln \frac{\rho}{\rho_0} \right) dx = \left(a^2 V - \frac{V^3}{3} \right) \Bigg|_{x_1}^{x_2} \tag{11}$$

From equation (11) you can find the speed A of the "shock wave" – the jump in the solution of system (1).

$$\frac{d}{dt}\int_{x_1}^{At}\left(\frac{V^2}{2}-a^2\ln\frac{\rho}{\rho_0}\right)dx+\frac{d}{dt}\int_{At}^{x_2}\left(\frac{V^2}{2}-a^2\ln\frac{\rho}{\rho_0}\right)dx=a^2\left(V_2-V_1\right)-\frac{V_2^3-V_1^3}{3}$$

The flow velocity before V_1 and V_2 after the shock wave (as well as the density ρ_1,ρ_2) are considered constant.

$$\left(\frac{V_1^2}{2}-a^2\ln\frac{\rho_1}{\rho_0}\right)A-\left(\frac{V_2^2}{2}-a^2\ln\frac{\rho_2}{\rho_0}\right)A=a^2\left(V_2-V_1\right)-\frac{V_2^3-V_1^3}{3}$$

$$A=\frac{a^2\left(V_2-V_1\right)-\frac{V_2^3-V_1^3}{3}}{a^2\ln\frac{\rho_2}{\rho_1}-\frac{V_2^2-V_1^2}{2}} \qquad (12)$$

Further, denoting the increments of speed $\Delta V=V_2-V_1$, density $\Delta\rho=\rho_2-\rho_1$ and pressure $\Delta P=P_2-P_1$; $\Delta P=a^2\Delta\rho$, and considering the characteristic asymptotic limit $\frac{V^2}{a^2}<<\frac{\Delta\rho}{\rho}\sim\frac{V}{a}<<1$, the symbol "~" denotes a value of the same order, we obtain:

$$\ln\frac{\rho_2}{\rho_1}=\ln\left(1+\frac{\Delta\rho}{\rho}\right)\text{ and }A\to\frac{a^2\Delta V}{a^2\frac{\Delta\rho}{\rho}}=\frac{\rho a^2\Delta V}{\Delta P}\to a\text{ at }\Delta P\to\rho a\Delta V$$

That is, we get the formula N.E. Zhukovsky $\Delta P=\rho a\Delta V$, corresponding to the shock wave speed equal to the speed of sound (independent of the flow speed V – this follows, for example, from (6) and means that the shocks go to the boundary of the solution area of problem (1-2)).

The fact that the indicated asymptotic limit is characteristic is explained by the conservation of all terms in the equations of system (1) for $\frac{\Delta\rho}{\rho}\sim\frac{V}{a}$ and $x\sim at$, which is identical to the following:

$$\frac{\partial}{\partial at}\frac{V}{a}+\frac{V}{a}\frac{\partial}{\partial x}\frac{V}{a}+\frac{1}{\rho}\frac{\partial\rho}{\partial x}=0\quad;\quad\frac{1}{\rho}\frac{\partial\rho}{\partial at}+\frac{V}{a}\frac{1}{\rho}\frac{\partial\rho}{\partial x}+\frac{\partial V}{\partial x}=0$$

An interesting consequence can also be deduced from equation (12): during subsonic flow in a "ring" pipeline, two shocks with magnitudes opposite in sign $\Delta V,\Delta\rho$ move at the same speeds towards the flow, that is, they do not interact with each other.

Indeed, if for one jump $V_2 < V_1 < a,\ \rho_1 < \rho_2$ and the function $f(V) = a^2 V - \frac{V^3}{3}$; $f'(V) = a^2 - V^2 > 0$ is increasing, then $A < 0$. Accordingly, for another jump $V_1 < V_2 < a,\ \rho_2 < \rho_1$, the same value $A < 0$.

Also from equation (12) you can learn the speed of a weak jump (discontinuity of the derivatives of the solution while maintaining the continuity of the solution itself) of system (1):

$$V = (V_2 + V_1)/2\ ;\ \rho = (\rho_2 + \rho_1)/2\ ;\ P = (P_2 + P_1)/2 \text{ at } \Delta V, \Delta\rho, \Delta P \to 0$$

$$A = \frac{\left(a^2 - \left(V_1^2 + V_1 V_2 + V_2^2\right)/3\right)\Delta V}{a^2 \ln\frac{\rho_2}{\rho_1} - V\Delta V} \to \frac{\left(a^2 - V^2\right)\Delta V}{a^2 \ln\left(1 + \frac{\Delta\rho}{\rho}\right) - V\Delta V} \to \frac{a^2 - V^2}{\frac{a^2\Delta\rho}{\rho\Delta V} - V} \to$$

$$\to \frac{(a - V)(a + V)}{\frac{\Delta P}{\rho\Delta V} - V} = a + V$$

Taking into account the signs of quantities in the Zhukovsky formula $\Delta P = \rho a \Delta V$, that is: the speed of the shock wave $a < 0$, if it moves towards the flow (if along the flow, then $a > 0$); $\Delta V < 0$ if the speed along the flow decreases, and vice versa $\Delta V > 0$, if it increases. The same goes for pressure. Thus, a weak shock is “carried away by the flow” in contrast to a “shock wave”.

Without taking into account the signs of quantities (without coordination with the direction of gas flow) $\Delta P = \pm\rho|a|\Delta V$, we obtain, respectively:

$$A \to \frac{(|a| - V)(|a| + V)}{\pm|a| - V} = V \pm |a|$$

That is, weak jumps (on the phase plane x,t) propagate along the characteristics of the system (1-2) “weak jump carried away by the flow”– this is a well-known result.

Practical applications.

First application: analogy-calculation (analogy-computing) devises implement the principle of modeling mathematical operations by physical effects. At $\alpha << 1$ the area of

solution of the problems (3) is a half-band $s_1 \in [-L/2, L/2]$, $s_2 \in [0, \infty]$ at constants boundary conditions:

$s_1 = -L/2 : V = V_0 + \Delta V_1$; $s_1 = L/2 : V = V_0 + \Delta V_2$;

$s_2 = 0 : V = V_0$; $U = U_0$, then the solution carried out in the area $\Omega = \left\{ -3L/2 < s_1 - s_2 < -L/2 ; L/2 < s_1 + s_2 < 3L/2 \right\}$ in form of the summator for velocity: $U = U_0$; $V = V_0 + \Delta V_1 + \Delta V_2$

Accordantly if constant boundary condition in the same half-band $s_1 = -L/2 : U = U_0 + \Delta U_1$; $s_1 = L/2 : U = U_0 + \Delta U_2$;

$s_2 = 0 : V = V_0$; $U = U_0 = a \ln \frac{\rho_0}{\rho_0} = 0$, then the solution in the area Ω is in form of the multiplicator for density: $V = V_0$; $U = U_0 + \Delta U_1 + \Delta U_2$

i.e. $a \ln \frac{\rho_0 + \Delta\rho}{\rho_0} = a \ln \frac{\rho_0 + \Delta\rho_1}{\rho_0} + a \ln \frac{\rho_0 + \Delta\rho_2}{\rho_0}$ that is $\rho_0 + \Delta\rho = \frac{(\rho_0 + \Delta\rho_1)(\rho_0 + \Delta\rho_2)}{\rho_0}$.

Suppose that you can control the speed of movement of charges at the ends of a nanowire of length L (by analogy – this is the speed V) and the charge density there (by analogy ρ), we also assume that you can measure the speed and density of charges in the middle of the nanowire. By setting the speeds $V_0 + \Delta V_1, V_0 + \Delta V_2$ at the ends, after a while $L/2a$ in the middle of the nanowire we will obtain the speed $V_0 + \Delta V_1 + \Delta V_2$ (analogy-calculation mesoscope summator). By setting the charge densities $\rho_0 + \Delta\rho_1, \rho_0 + \Delta\rho_2$ at the ends, after a while $L/2a$ the density in the middle of the nanowire is obtained $(\rho_0 + \Delta\rho_1)(\rho_0 + \Delta\rho_2)/\rho_0$ (mesoscope multiplicator). When $L \approx 3 \cdot 10^{-8} m$ time of performing addition and multiplication operations by analogy-calculation mesoscope devises (theoretically) is of the order of $L/2a \approx 10^{-13} s$ [3].

Secondly application: Considers the ring quantum current in closed linear polymolecules, which are obtained nanotechnologically and also occur in nature, for example, mitochondrial DNA (mtDNA). An analogue of the speed of propagation of disturbances in an electron gas (the electron speed of sound), as noted above, is the quantity $a_e = \delta_e \sqrt{\frac{e \rho_e}{m_e \varepsilon_0}} \approx 1.41 \cdot 10^5 \frac{m}{s}$ (see [2]).

Here, the electron density $\rho_e = 10^8 \frac{Q}{m^3}$, as well as the radius of the nanowire $\delta_e = 10^{-10} m$, are quantities of precisely this order. Also in [2] it is shown that radio waves in the terahertz range (with frequencies of the order of $\nu = \frac{a_e}{L_e}$) can be both emitted and received by ring polymolecules of mtDNA (having a characteristic length $L_e \approx 10^{-7} \div 10^{-6} m$).

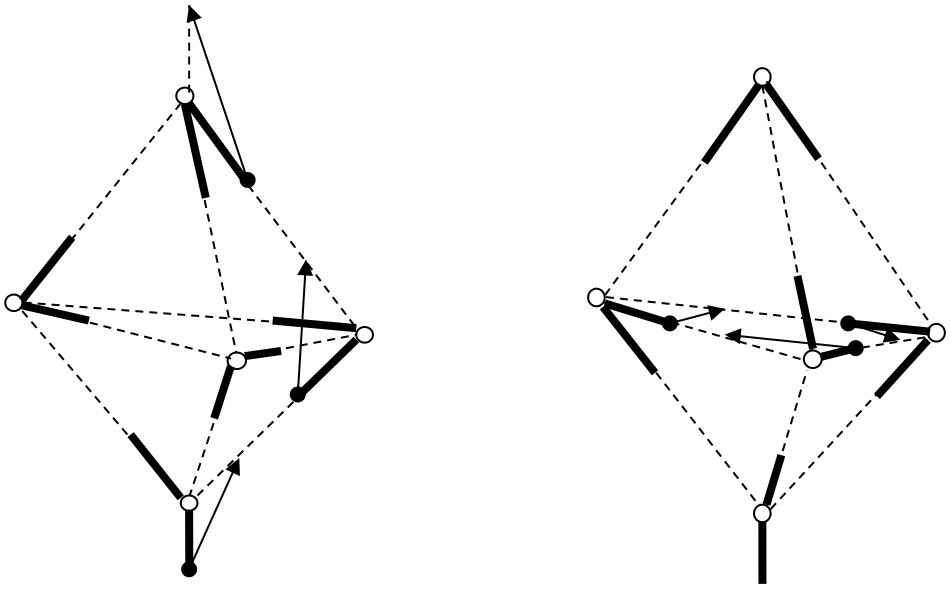
Here it is also appropriate to mention the inevitability of weak or strong jumps (for a solution of an unsteady gas flow system) in a closed "ring" quasi-one-dimensional structure [1], like of the mtDNA nanowire. The therapeutic effects from exposure to terahertz radiation already have many examples [5 – 6], and this experience is increasing, although there is not yet a general understanding that the root cause of this effect is the reception – retransmission of terahertz radiation by quantum ring current effect in the ring polymolecules mtDNA.

Thirdly application: the one–dimensional periodic chained structure of water consisting from five–molecular repeating parts formed by the Bernal - Fowler rules (see on figs. 1–3 – " o " – designates atom of oxygen; solid line is intermolecular communications with atoms of hydrogen). Angular values between hydrogen communications in four molecules of water are assuming to equal $\pi/3$. In work [7] such structure named as "water sublime" (sublimer).

The existence of such a structure of water is possible only in special conditions created artificially, for example, inside a carbon nanotube, and in biological objects, for example, inside the porous-tubular shells of cereal seeds. Transitions between quantum states of such a quasi-one-dimensional molecular structure occur through the displacement of H^+ "hydrogen bonds" (they have three types – see Fig. 1,2,3 "*s=1,2,3*" and difference in the number of displaced atoms). A similar type of charge transfer is also observed in DNA molecules, and is sometimes called "protons tunneling" [8].

Experiment [9] showed that the response of sunflower seeds (studied by electrical impedance spectrography) to alternating (exciting) voltage with a frequency of $n_0 = \frac{1}{T} = 600\ Hz$ has a frequency $100 \div 200$ times higher. Let us denote the average value of this frequency over the spectrum as $n \approx 10^5\ Hz$ (see Fig. 4 – modulated voltage $U_0(t_{\mathrm{mod}T})$ in the circuit – lower graph and "response" – upper graph). The response or "reflection" $U(t_{\mathrm{mod}T})$, in the form of voltage fluctuations in the circuit due to the excitation of the object under study, is obtained by

subtracting from $U_0(t_{\mathrm{mod}T})$ the sinusoidal voltage generated by the source with a frequency of 600 *Hz*.



Change of orientation of free hydrogen Transition type $s = 1$

Figure 1

The totality of the results of this experiment can be explained on the assumption that the response in the form of electrical voltage taken from the contacts installed on the "object" (sunflower seed) arises precisely as a result of the wave-like process of "change of orientation of free hydrogen". Let's imagine the dynamics of this process – see Fig. 1–3.

The last sublimer in the chain changes its orientation (pushes the "foot of free hydrogen" into the upper – neighboring sublimer), which also changes its orientation, forces the next one to reorient, etc. – a wave of orientation change runs along the chain. At the end it is reflected, that is, the outermost sublimer, having changed orientation, produces a reverse reorientation, and a wave of similar reorientations runs along the chain in the opposite direction.

At the edges of the chain, due to the applied electrical potential difference, hydrogen gives up an electron to the outside, becoming a proton, or vice versa - being a proton, it accepts an electron. Thus, a wave of orientation change with a violation of the electro-neutrality of sublimers can be considered as a "mechanism" of charge transfer fundamentally similar to the Grotthus mechanism (Theodor von Grotthus) – the movement of a proton in dissociated water: a proton binds to a water molecule to form hydronium ions – H_30^+ or $H_20 \times H^+$. Such ions, in turn, can bond through hydrogen bonds with other water molecules, forming, for example, Zundel $(H_20)_2 \times H^+$ and Eugen $(H_20)_4 \times H^+$ cations [10].

Let us evaluate the orders of physical quantities, the main one of which is the electron density, determined by the following values:

Radius of the nanotube $\delta_H = 3 \cdot 10^{-10} m$, inside of which there is a chain of water-sublimers; nanotube length per sublimer $L_H = 1.2 \cdot 10^{-9} m$; the number of sublimers N combining into one elementary volume "gaseous particle", the totality of which is considered as "an element of a continuous medium carrying an elementary charge":

$$\rho_H = \frac{e}{\pi \delta_H^2 L_H N} \approx \frac{1.60202 \cdot 10^{-19}}{3.1415 \cdot (3 \cdot 10^{-10})^2 \cdot 1.2 \cdot 10^{-9} N} \approx \frac{4.716 \cdot 10^8}{N} \frac{Q}{m^3}$$

Here $m_H \approx 1.6734 \cdot 10^{-27} kg$ is the mass of the hydrogen atom, then the value of the speed of propagation of disturbances (orientation change waves) along the sublimers chain, determined by analogy with a quantum current nanowire [2]:

$$a_H = \delta_H \sqrt{\frac{e \rho_H}{m_H \varepsilon_0}} \approx 3 \cdot 10^{-10} \sqrt{\frac{1.60202 \cdot 10^{-19} \cdot 4.716 \cdot 10^8}{1.6734 \cdot 10^{-27} \cdot 8.854304 \cdot 10^{-12} N}} \approx \frac{2 \cdot 10^4}{\sqrt{N}} \frac{m}{s}$$

The frequency of double passage of reorientation waves along the chain of sublimers is equal to the response frequency (averaged over the entire response spectrum and over time – between the beginning of excitation and the bifurcation of the signal with its subsequent complete chaotization).

$$10^5 Hz \approx n = \frac{a_H}{2 L_S} \approx \frac{2 \cdot 10^4 Hz}{2 \cdot 10^{-2} \sqrt{N}}$$

Here, the length of the sublimers chain is assumed to be equal $L_S = 10^{-2} m$, taking into account the fact that they occupy the entire length of the sunflower seed shell. The shell has a tubular-porous structure with an internal diameter of the tubes of the order of $1nm$, where water is structured as the sublimer chains. As a result, the order of magnitude is estimated $N \approx 100$ – this is the number of sublimers, conditionally united into one elementary volume – "a particle of a gaseous continuous medium" (order of error for the approximation by a continuous medium $\frac{L_H}{L_S} N \approx 10^{-5}$). The magnitude N has order of sublimer mass in carbon units ≈ 90.

Let us further note the following observations, which can be clearly seen from the video recordings of the experiment –the frequency of response oscillations first decreases with increasing amplitude, and after passing through the middle of the signal, vice versa –the amplitude decreases, the frequency increases. Then the signal "splits into two", and the

temperature increases. Decay is the appearance of the next signal in time, and the next signal is slightly shorter in duration. Let us try to explain the combination of these factors “in the language of waves of orientation changes” of water-sublimers chains.

The change in orientation of the sublimer according to the energy transition (based on the difference between the energies of quantum states) is close to the change of state shown in Fig. 1 (in both cases three hydrogen atoms are displaced – transition type *s=1*). Other types of transitions (with the displacement of four or seven hydrogen atoms – *s=2,3* – Fig. 2 and 3) are more energetically expensive. Based on this, we can conclude that if changes in orientation and transitions of the *s=1* type occur simultaneously in a chain of sublimers, then these processes seem to interfere (do not interfere with each other). Consequently, the presence of transitions of type *s=1* does not change the speed of the orientation change wave running along the chain.

Transitions of types *s=2,3* are accompanied by such displacements of hydrogen atoms that are also observed when changing orientation; therefore, these processes cannot occur simultaneously, and the presence of transitions of type *s=2,3* slow down the wave of reorientations.

During attenuation, the energy of thermal movement dissipates, the surrounding tubular structures cool down (they give off energy to the space external to the seed in the form of thermal radiation, corresponding in the spectrum to a lower temperature than during heat exchange with sublimers chains). While the chains straighten (their transverse vibrations calm down), and the process of wave motion of changes in their orientation is again excited. Thus, the signal splits into two. The next signal has a shorter duration, since its initial temperature is higher, and less time is required for heating, at which time the reorientation wave fades.

With an increase in the intensity of the exciting voltage, the decay time – cooling – increases, that is, the “time distance” between successive excitation signals of water-sublimer chains increases. This is accompanied by an increase in temperature at a sensor located outside the object and then, when the temperature is so high that the chains can no longer cool down and straighten so that the reorientation waves can synchronize, the response of the object with a clearly organized structure disappears – the process becomes more chaotic.

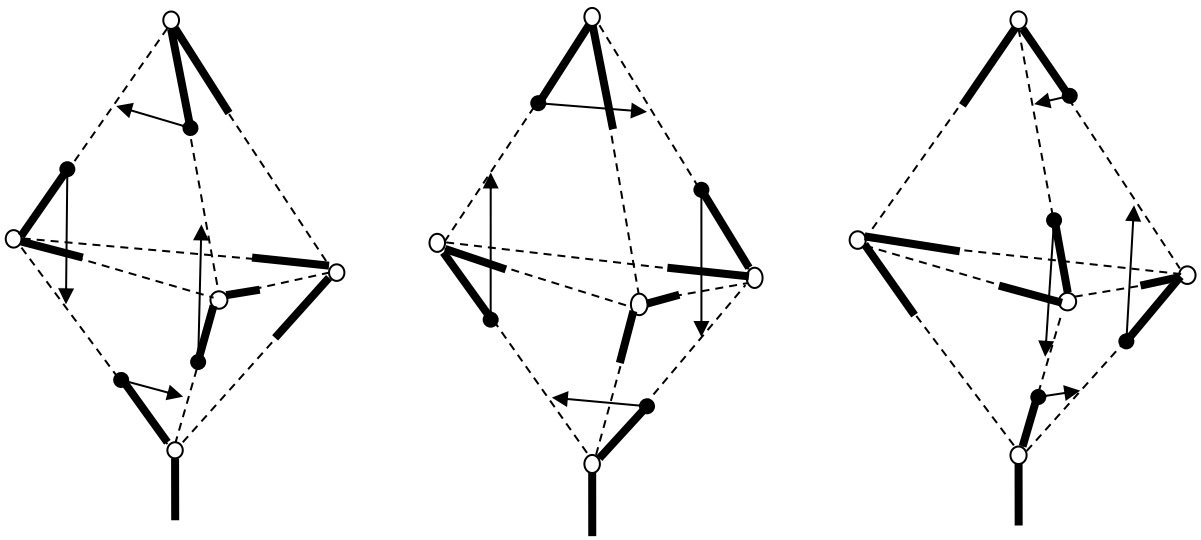


Figure 2. Transitions type $s = 2$

At the same time, the energy of the process increases (in the sense of an increase in the difference in energy levels during quantum transitions), and this leads to the fact that in addition to transitions *s=1* and reorientations, transitions of types *s=2,3* appear, which are "built in" between transitions *s=1* and between reorientations, thus slowing down the wave speed. In the video frame of the experiment, this manifests itself as a decrease in the response frequency with increasing amplitude. This increase in molecular motion leads to an increase in temperature, which in turn leads to the emission of chains of energy in the thermal spectrum.

When energy is released in the form of heat, the chains again return to wave motion with the possibility of only transitions of the *s=1* type between changes in orientation - the frequency increases, the amplitude decreases. This can be imagined as the conversion of electricity into heat through a specific "wave" molecular movement of water-sublimer chains.

The heat given off leads to increased molecular motion in the immediate environment of the chains (they cannot be in direct contact, but must be located inside tubular molecular structure, which are present in the shell of a sunflower seed). The increasing molecular (thermal) motion of the surrounding structures affects the chains, disrupting their linear configuration (dynamically bending, that is, exciting them transverse bending vibrations), and this leads to the attenuation of the waves of reorientation of sublimers, and the operation of the object as a converter of electromagnetic energy into heat [11] some time fades away.

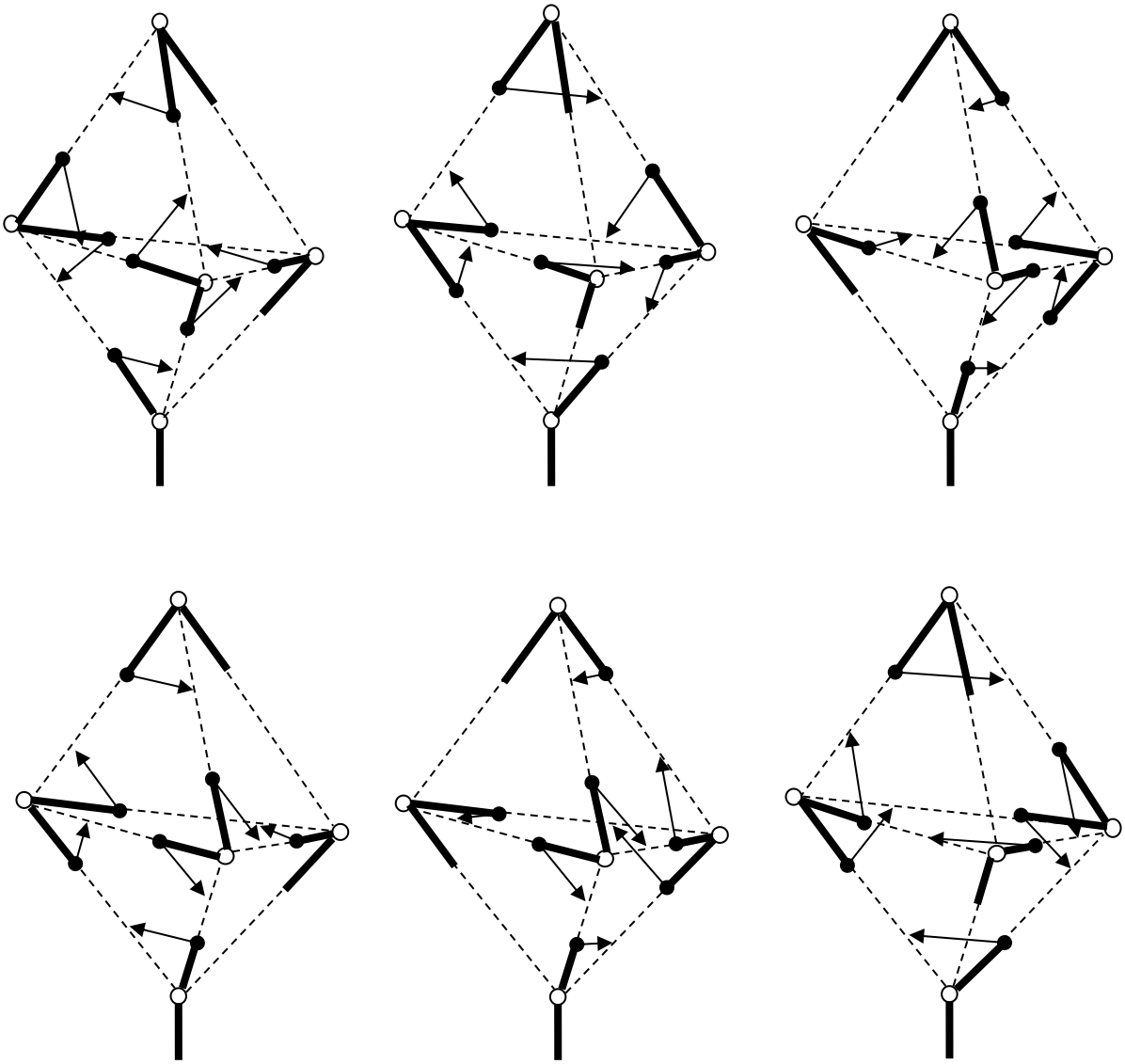


Figure 3. Transitions type $s = 3$

Conclusion.

Provided that the solution (of one-dimensional unsteady gas flow system) is periodic in the spatial coordinate, it is also periodic in time; accordingly, the phase manifold is mapped to the 2D torus in four-dimensional space. This theoretical result, which essentially consists in the presence of a non-degenerate topological structure family of the solution of the system, indicates that the condition of constant speed sonic, with some deviations from it, should not violate the topological properties of the solutions. Additionally, this causes some applications:

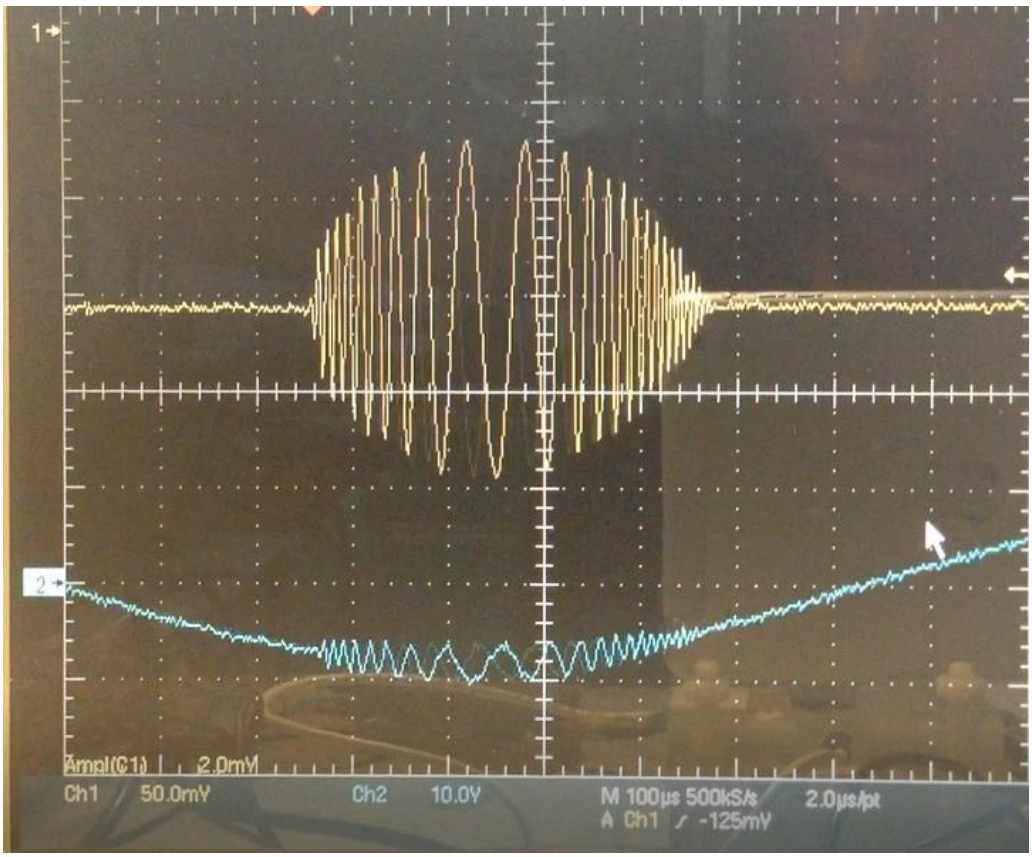


Figure 4. Study of sunflower seeds using electrical impedance spectrography (lower graph – exciting voltage 600 *Hz*; upper – response voltage)

Firstly, from this we can conclude that when gas flows in a closed "ring" pipeline, weak or strong jumps (generalized solutions excluding the trivial case – when the solution is constant) are inevitable. Secondly, similar ring structures at the polymolecular level (and the corresponding flows of electron gas – quantum ring current) explain the effect of receiving and relaying terahertz radiation from mtDNA (within the mitochondrial matrix and between these organelles). Thirdly, the analogy of the propagation of elastic waves in quasi-one-dimensional molecular structures (such as a chain of water sublimers in the tubular shells of seeds or inside carbon nanotubes) satisfactorily explains the effects of the conversion of electricity into heat (or terahertz radiation), observed in experiments, and which cannot be fully explained based on from other reasons.

The presence of tubular channels in the sunflower seed shell (as in wood) is beyond doubt. It is known that, depending on water saturation, the electrical resistance of wood varies over a very wide range ($10^6 \div 10^{15} \Omega \cdot m$), and this is certainly due to the special structure of water in the tubular channels between the fibers. The calculations presented in this work indicate a possible variant of water structuring in such conditions (natural biological or artificially created – inside carbon nanotubes), and this explains the results of the experiment.

In modeling radio frequencies that fall in the terahertz range, it is fundamentally important that it is impossible to make a similar assessment in the representation of the electrically conductive ring polymolecule mtDNA as a micro-oscillatory circuit (it is impossible to introduce analogues of inductance and capacitance). An alternative is to represent the effect of a quantum ring current in a continuum model, and based on this estimate the frequency as the ratio of the speed of propagation of the disturbance to the length of the mtDNA ring. What is fundamentally important here is the inevitability of weak or strong jumps in the solution (of a system of one-dimensional unsteady gas flow), that is, analogues of compression and rarefaction waves.

The presented work highlights the operating principle of mesoscopic analogy-computing devices, the implementation of which still raises many questions. However, this area of nanotechnology is rapidly developing, for example, the method of constructing polymolecular biological structures such as “DNA origami” or single-atomic chains of precious metal atoms – these molecular structures have a quasi-one-dimensional structure and are conductive.

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