# Some Aspects of Rotated Detonation Waves

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## 1 Brief history of investigation of rotated detonation waves

Burning phenomena are known millions years, but the gaseous detonation was investigated only about 130 years ago (for example, Mallard and Le Chatelier 1881, Berthelot and Vieille 1883). One can read the overviewed papers on history of detonation investigations - Bauer et al. 1991, Manson and Dabora 1993, Lee 2008. After its discovery the detonation wave (DW) was considered during long time as plane wave without any internal structure. It was great surprise about 80 years ago when the unusual regime of DW propagation in tube of round cross-section with spiral trajectory of unknown element on inner smoked wall and with strong pulsation of unknown luminosity front (tail) in detonation products were observed by Campbell and Woodhead (1927). This regime was named as spinning DW and for a long time it considered as exotic detonation regime. The wellknown term of "transverse wave" (TW) for spinning configuration appeared about 65 years ago (Voinov 1950). Spinning DW in round tube is the unique stationary process of wave propagation with single transverse wave on the DW front, which axially rotates along internal surface of tube wall. The structure of spinning DW (as in modern point of view) was solved firstly by Prof. B.Voitsekhovsky (1957). His experimental photo of self-luminescence of spinning DW with bright transverse wave became classical (as on Fig.1).

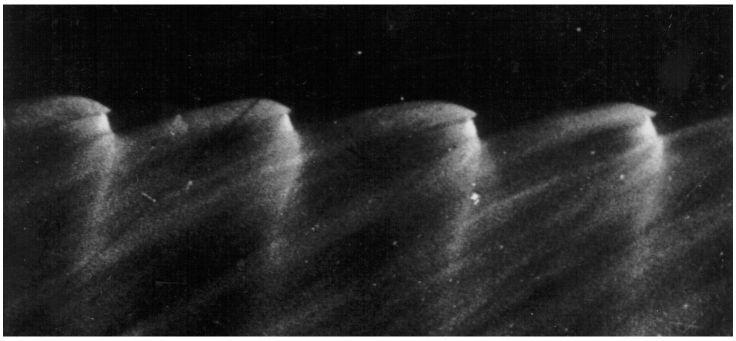


Fig.1. Streak record of spinning DW – special photography on moving film across the slit paralleled to tube axis and at oblique position of axis of photo-camera (the details – see Voitsekhovsky e.a. 1963).

## 2 Application of detonation regime

The increased interest to use of a detonation process in various technological devices and, in particular, at development of the concept of detonation engine (DE) is stipulated by classical conclusion that from every possible modes of burning of a combustible mixture the regime of selfsustained detonation (the ideal Chapman-Jouguet wave) is characterized by minimum irreversible losses. The point D of a tangency of the Michelson-Rayleigh line ODS to a detonation branch 1 of adiabatic curve of energy-release Q = const corresponds to minimum growth of an entropy $\Delta S_D$=min (isentropic curve is tangent to an adiabatic curve from below) on a comparison with any other points ($\Delta S_V$ or $\Delta S_P$). The higher losses are inherent for combustion modes (laminar and turbulent) on a comparison with the C-J detonation mode: the point F of a tangency of the Michelson-Rayleigh line OF to lower deflagration branch corresponds to maximum growth of an entropy (in F isentropic curve is tangent to an adiabatic curve from above - $\Delta S_F$=max). $\Delta S_D$=min is the first advantage of detonation mode.

The second advantage is the maximum high pressure of a detonation products $P_D$ on a comparison with traditional combustion, where a final condition is close to point $P_P$ (to be in general agreement with condition P = const) or to point $P_V$ (burning at condition V = const).

Only these two advantages of detonation burning allow get positive profit at consequent expansion of DW-products.

Additional advantage connects with huge velocities of a mixture burning in a detonation wave (DW) and the highest power (energy in unit time) of detonation energy-release, unattainable for combustion conditions.

# 3 The results and problems

To the present time for a realization of idea of burning of a combustible mixture in detonation modes the set of various devices is offered, including numerous model scheme of a detonation engine (see, for example, bibliographic lists in the reviews of Nikolaev a.o (2003) and Roy a.o (2004)). The basic scheme are the next:

a) «Weapon» schema of a pulsing detonation engine (PDE);

b) The schema of supersonic pulsing detonation ramjet engine (PDRJE);

c) The schema of a mixture burning with the help of steady rotating detonation wave.

The latest schema of a detonation engine with steady rotating DW (RDE) is original alternative to scheme of PDE. Some important aspects of rotated DW are discussed in this report: correlation of acoustic characteristics of reaction products with rotation velocity of TW; velocity deficit and energy-release; multifront system of rotated TWs; streak-records trajectory of rotated TW on moving film…

Prof. N.Manson (1946) was the first, who proposed the acoustic theory of spinning detonation. He assumed that the TW rotation is connected with acoustic vibration of detonation products. For spinning DW with single TW, its axial velocity $D_{\perp}^{S} = 1{,}84 \cdot c$ , where c is the sound speed in detonation products, and 1.84 is the value of major root of the Bessel function of the first order, which describes the radial component of velocity potential of a gas products for 2D acoustic equation. The time of one revolution of TW is $t^0 = \pi \cdot d / D_{\perp}^{S}$, d is the tube diameter. The trajectory of spinning TW represents a spiral line with the step $\lambda = D_{II} \cdot t^0 \cong \pi d$ and with the slope to the tube axis $tg \cdot \varphi_S = D_{\perp}^{S} / D_{II} = 1{,}84 \cdot c / D_{II} \cong 1$, i.e. $\varphi_S \approx 45^o$, since $c / D_{II} \cong 0{,}55$, $D_{||}$ is the longitudinal (along the tube axis) velocity of DW. The Manson acoustic theory predicts the change of main acoustic frequencies at change of volume of products, for example with the help of central coaxial core (typical case for detonation engine). In coaxial gap the spinning regime was observed also, but the tail frequency differs from value typical for tube.

The idea to burn mixture in detonation mode appears many years ago. In latest years many investigators from different countries are connected with problem of pulse detonation engine (PDE), when DW as cyclical process propagates along the tube. Prof. B.Voitsekhovsky was the first who proposed to burn the mixture in detonation mode with the help of rotating waves, likely transverse wave of spinning configuration (Voitsekhovsky et al. 1963). The engine with stationary rotating DW is alternative to pulse detonation engine. How stabilize the rotation of TWs in some plane (without propagation along the tube)?

At case of immovable mixture transverse wave of spinning configuration moves along spiral line because of simultaneous rotation and propagation along axis. The rotation of TW can be realized in stationary plane if mixture moves as flow with velocity to be equals to propagation velocity of DW along axis. But this method can not be realized in practice because such flow can be ignited non-controlling in boundary layer near tube wall, because the flow stagnation temperature exceeds the self-ignition temperature. So the stabilization of rotating wave usually was realized with the help of the injection nozzles, located in some plane. At this the mixture components can be injected as along the axis, as in radial direction (from centre to outside or from outside to center). The schema of circle channel of inner radius R1 and outer radius R2 is presented on Fig.2 with mixture burning in circle channel by the wave, rotated axially along the channel. The detonation mode of mixture burning with the help of stationary rotating detonation waves was investigated effectively in our Institute up to now (Zhdan and Bykovsky 2006).

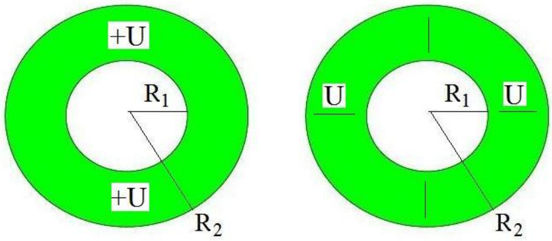



Fig.2. The idealized schema of a mixture burning in the ring combustion chamber with the help of steady rotated TW and typical view on channel cross-section for investigation of rotated TWs: a) – left – at injection of mixture along the axis (+U); b) – right – at injection of mixture along the radial direction (from centre or to center).

It must be marked, that in a rectilinear pipe of a round (constant) cross-section the regime of stationary DW propagation along pipe axes with the single transversal wave (TW), rotating along an interior concave surface, can be realized at lowering of initial pressure up to some limiting value. The spinning detonation is the limiting regime with the velocity for different mixtures on level $D_S=(0.8\div1.0)D_0$. The velocity deficit is equivalent to deficit of energy-release from point of view of ideal ZND–model or to loss of energy into walls. Taking into account the complex form of spinning configuration it can concluded, that one-dimensional model is incorrect for description of spinning detonation and 3D-model must be used at numerical modeling. It must notice about some aspects of spinning DW.

What is the space structure of spinning DW, especial near the tube axis? This problem was investigated experimentally by many investigators and at last time – numerically (Tsuboi and Hayashi 2006, Khasainov a.o. 2008, Manuilovich a.o. 2013, Aksenov a.o. 2013,…).

The condition of spinning regime as the limiting regime of steady DW-propagation can be written as $a = \pi d_S$, here *a* is the cell size and *ds* is the diameter for the limiting regime - spinning DW. So, if the dependence $a(P_0)$ for explosive mixture are known (for example, from calculation), then the diameter $d_S$ may be determined according to last formula.

It must be marked especial, that the spinning detonation was observed not only in tube, but also in the coaxial channel. If you look along the tube (across transparent window on tube end), then you observe the circle layer of radius $R_1$ and $R_2$ and the rotated luminosity zone among the channel boundaries. With the help of optical system the tube cross-section can be focused on film as image projection. At rotation of luminosity point in coaxial channel its image will create on moving film the trajectory, similar to cycloid from classical task about trajectory of some points at wheel rolling along the plane. If mixture was burned in cylindrical front of laminar flame and the film of photo-camera moves with constant velocity, then one can see the streak records as on Fig.3 – the light layer as trajectories of luminosity circle. Because the circle flame front is the boundary between cold initial mixture and hot reaction products, it is evident that in such system the instability of laminar cylindrical flame will be grow and axial acoustic disturbances of hot products will generate the shock wave disturbances in cold mixture. Because of radial and axial instability the luminosity point of rotated wave will produce the complex trajectory of variable radius, located among circle boundaries of channel ($R_1<R<R_2$).

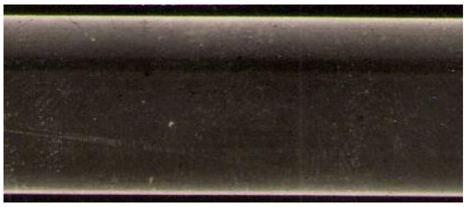
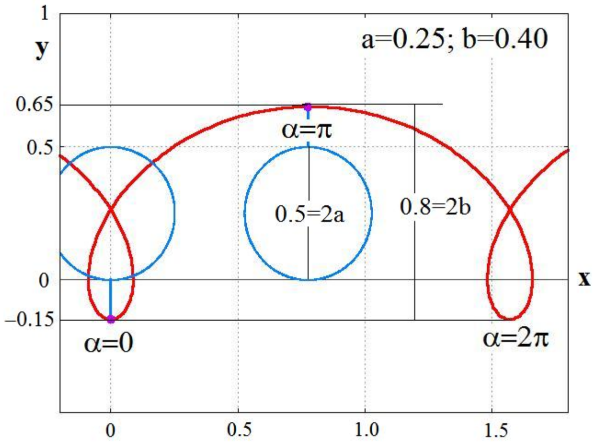


Fig3. The streak-records of mixture burning in cylindrical laminar flame.

Let us take an advantage the classical task about wheel rolling along the plane and trajectory function of point A (RA=a – wheel radius, blue circle) and point B (RB=b>a – red line) – see Fig.4 as example for a=0.25 and b=0.40.



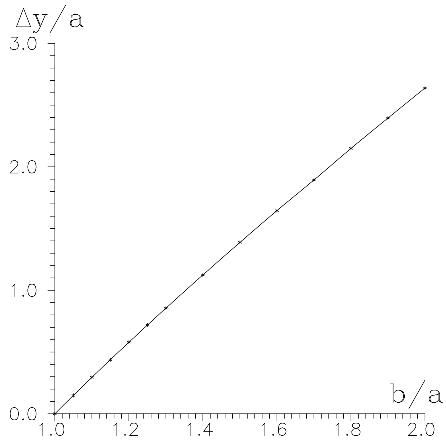




Fig.4. Typical cycloid trajectory of point b at wheel rolling of radius a along plane.
Fig.5. The depth of cycloid loop as function of position of point B on rolling wheel.

The parametric system for trajectory of point B is next:

$$x = a\alpha - b\sin\alpha$$
$$y = a - b\cos\alpha \quad ,$$

α – an angle among vertical line between point of contact of wheel with plane and line OB. The equation of trajectory of point B in (x,y) plane is the next:

$$\frac{x}{a} = \arccos\frac{a-y}{b} - \sqrt{\frac{b^2}{a^2} - 1 + 2\frac{y}{a} - \frac{y^2}{a^2}} \ .$$

For determination of extremum of this function we use additional relation:

$$\frac{dy}{dx} = \frac{dy/d\alpha}{dx/d\alpha} = \frac{b\sin\alpha}{a - b\cos\alpha} \ .$$

The condition $dy/dx = 0$ gives the minimal and maximal y-values of function, so one has the solution $\sin\alpha = 0$ , and $\alpha = \pi n$ at $n = 0,1,2,...$ The condition $dy/dx = \infty$ gives the vertical asymptote, so $\cos\alpha = a/b \le 1$ is the x-solution.

The most bright peculiarity of trajectory at b/a>1 is the cycloid loop. Its maximal depth $\Delta y = y_2 - y_1$ is determined at $x = 0$. Then $\alpha = b/a\sin\alpha$, and the evident solution is $\alpha = 0$, what gives the root $y_1 = (a-b) \le 0$ at $\alpha = 2\pi n$ $n = 0,1,2,...$ The $y_2$-root can be determined by numerically from the same equation. On Fig.5 the depth of the cycloid loop as function of b/a value is presented and one can see their near-linear dependence.

As mentioned above, the luminosity point in real channel not propagates along the circle of fixed radius, so the analogy of the trajectory of rotated TW with the trajectory of wheel rolling along plate is quite approximate. On Fig.6 the process of initiation and initial stage of formation of rotated TWs is illustrated as streak-record of circle channel (as on Fig.2) on moving film.

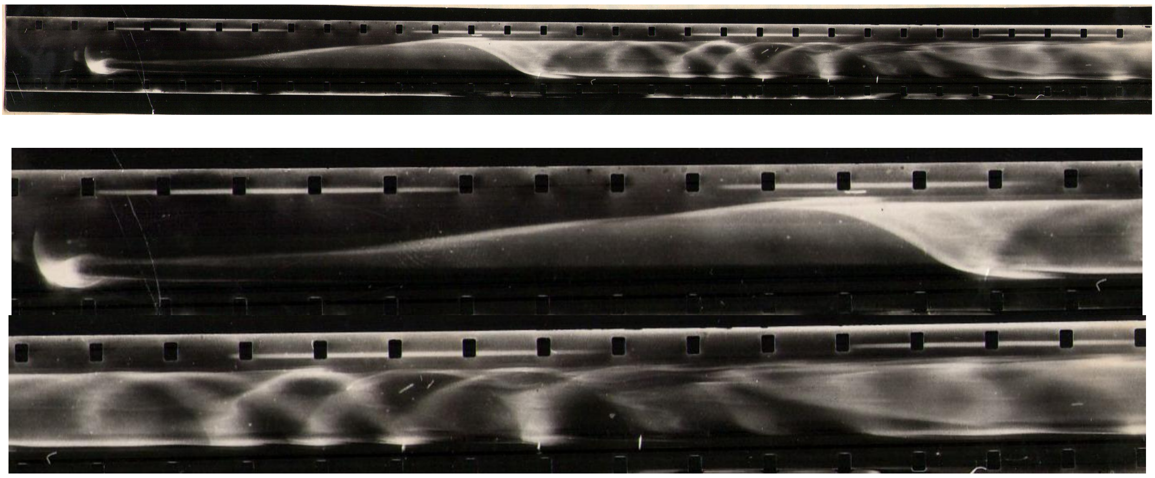


Fig.6. Original and its two increasing one-half fractions.

After initial period the rotation of TWs becomes steady and one can see these pictures on Figs.7-8 for case of 3 and 4 TWs on total channel length $2\pi R$. There are two important aspects of rotated TWs:

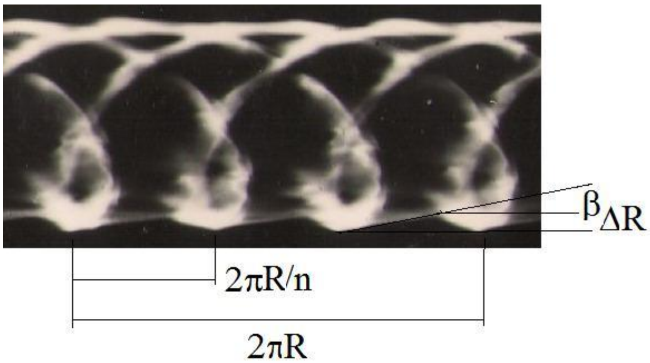



Fig.7. Trajectories of 3-head rotated detonation (n=3)

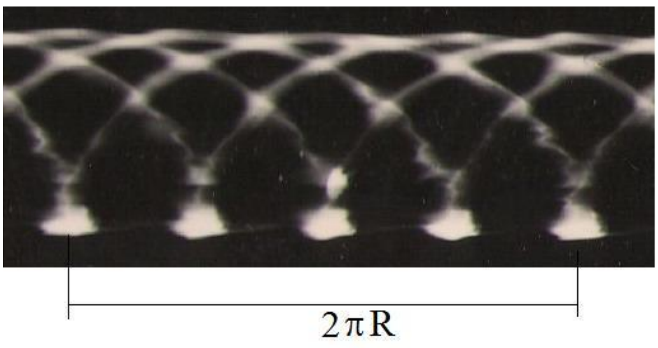



Fig.8. Trajectories of 4-head rotated detonation (n=4)

first – the cycloid loop; second – the inclined line among neighbouring cycloid loops (the angle β on right of Fig.7). One can see, that the depth of loop for n=3 equals approximately to half of total luminosity strip. To such depth of loop the value b/a≈1.35 from task about wheel rolling along plate (see Fig.5). For n=4 the depth of loop is much lower (fig.8), through the channel sizes become unchanged. Why it is? It is unclear for the present. What radius of circle channel corresponds to radius of rolling wheel?

The vertical size of luminosity area on photo (among the most remote points) is equal to external channel diameters ($2R_2$), divided on reduction ratio k of optical system. If the film moves with velocity V relatively the image of circle channel, then its equivalent to shift of channel relatively to immobile film with velocity W=kV. If the axial velocity of rotated TW denote as D and choose D=W=kV, then the special type of registration of moving bright point on moving film can be realized (so called the regime of whole compensation of velocities of object and its image). In this case the sharp pattern of luminosity zone without any image blurring is resulted. Such regime of whole compensation one can see on lower part of photo, so the inclined line characterizes the relation among the velocity of input flow of mixture U and velocity of rotated TW D: $\mathrm{tg}\beta = U/D$. It must be mentioned especially that it seems easy to produce the rotated TWs propagated with the velocity of ideal C-J detonation $D_0$, but as a rule the velocity of rotated wave D is less $D_0$ and D-value is closed to value of sound speed of detonation products c (usually $c \approx 0.45D_0$). Experimental values are equal $D_3$≈900 m/s and $D_4$≈800 m/s, so for given photo U≈D/6≈150 m/s is subsonic ($U<c_0$, $c_0$ – sound speed of initial cold mixture).

The classical spiral trajectory is typical for spinning detonation with single transverse wave. The rhomboid cell structure appears in tube when two TW (as minimum) exit on detonation front and such TWs move in opposite direction and collide periodically (as in multifront DW). It is interesting, that although the regime with rotation of both TWs in one direction is possible theoretically, but it not observed experimentally, probably because of nonconservation of the moment of impulse?

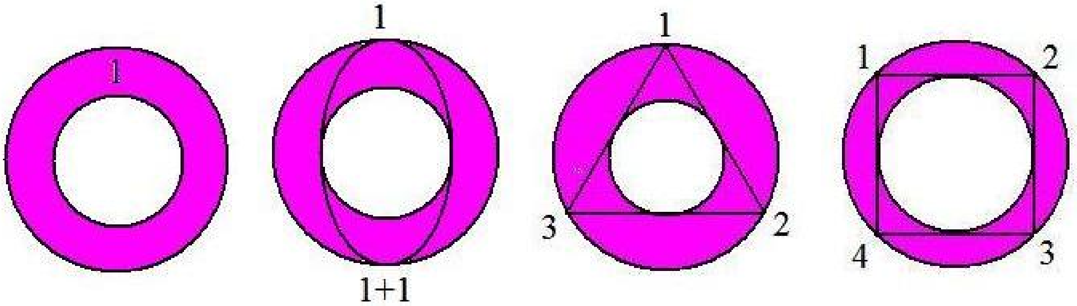



Fig.9.

The rotation of TW in spinning detonation has the acoustic nature, connected with hot products. From acoustic point of view with straight path it is imaged easy the steady picture with 3 and 4 acoustic heads (3-d and 4-th schema on Fig.9). The schema with 3 heads is realized at $R_2 = 2R_1$, with 4 heads – at $R_2 = \sqrt{2}R_1$. The schema with 2 heads is impossible in coaxial channel for straight path, but can be imaged for curvilinear path, for example, at elliptical trajectory (2-d schema on Fig.9). At this the channel radiuses $R_1$ and $R_2$ play role of minor and major semiaxis.

There are many interesting task for future investigations, devoted to rotated detonation waves.