New insights into the reactionary zones excited-state programming by plasma-acoustic coupling mechanism for the next-generation small satellite solid propulsion systems

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Abstract. Small satellites are changing the game for deep space missions because can work together in a fleet to take on more complex missions. Smart control by excited-state of the reactionary zones is one of the keys to access to the properties of the solid propellants reactionary zones. In particular, the self-organized wave patterns excitation occurs at excited-state of the reactionary zones. Use of the plasma-acoustic coupling mechanism is one of the advanced ways to access to the properties of the reactionary zones: the scale and localization of the induction and energy-releasing areas. On the base of detailed analysis we suggest the new concept for the reactionary zones programming by the plasma arc force field emitter with application of the self-organized wave patterns excitation phenomenon. The innovative aspect of this concept is the plasma-acoustic coupling mechanism that transforms the input electrical energy into the directed acoustic energy. Suggested concept for manipulating by self-organized wave patterns in the reactionary zones with using of the plasma arc force field emitters and new generation of the electrically activated solid propellants is opening the door for completely new ways for producing extremely small thrust impulses for the extra-precise attitude control of the small satellites.

1. Introduction
There is growing demand for in-space propulsion systems with extreme and precise thrust control that enable small satellites to achieve attitude and orbit control, orbital transfers, and end-of-life deorbiting. Small satellites are changing the game for space missions because can work together in a fleet to take on more complex missions. The constellation of the small satellites can serve as a deep-space-capable research spacecraft.

Solid propulsion systems (SPS) continue to be a reliable way to provide thrust and are used in almost every Earth-to-orbit launch capability. Controllable SPS combine the simplicity of solid engines and the thrust variation ability of the liquid and hybrid engines. More advanced SPS can not only be throttled but also be extinguished and then re-ignited by controlling the nozzle geometry or through the use of vent ports. A new generation of technologies is expanding solid propulsion capabilities and increasing their relevance for versatile and maneuverable micro-satellites with safe high-performance propulsion.

Electrically activated solid propellant rocket motor thrusters is a subject of extensive research. In this method electric fields are exploited to regulate ignition and thus throttle of solid propellants. These propellants, based on ionic salts, are basically inert until an electric current is passed
through them at which point they exhibit an electro-chemical reaction. Such kind of propellants are collectively referred to as “electric propellants,” or simply ePropellants (by Digital Solid State Propulsion, LLC, Reno, NV), [1]. ePropellants could even be 3D printed into the structure of the small satellite enabling even more propellant capacity. The range of applications for this game changing technology includes attitude control systems and a safe alternative to higher impulse space satellite thrusters.

Both experiments and theory confirm that the micro- and nano- scale oscillatory networks excitation in the solid propellant (SP) reactionary zones is a rather universal phenomenon [2, 3]. The analysis of experimental data shows that the macro-scale phenomena at the SP combustion are result of self-organizing and self-synchronization of the micro- and nano- scale oscillatory networks in the SP reactionary zones. This hypothesis is supported by the experimental data provided by Japanese research team [4-6].

This data has been obtained during study of oscillation and synchronization in the simple experimental system, containing a set of paraffin candles. Discovered in the 17th century by Christian Huygens, self-synchronization was observed in physics, chemistry, biology and even social behavior, and found practical applications in engineering. This phenomenon are universal and can be understood within a common framework based on modern nonlinear dynamics.

The micro- and nano-scale oscillatory networks arising in the SP reactionary zones has a significant influence on physical and chemical processes and on controllability of ignition and combustion processes.

Control by self-organized wave patterns excitation is one of the keys to access to the properties of the SP reactionary zones.

Behind excitation of the micro- and nano- scale oscillatory networks and wave patterns exists the universal Cytmathics phenomenon.

2. Self-organized wave patterns excitation phenomenon in the reactionary zones

During the last decades, researchers have observed the excitation of the micro- and nano- scale oscillatory networks in the reactionary zones of the energetic materials (EM) and the presence of micro-torches over the EM burning surface, (see figure 1) [7]-[11].

![Figure 1. Typical shape of the extinguished burning surface of the pyroxylin sample [7], [9], [10].](image)

As the experiments show, the EM burning surface has a complex of inhomogeneous and non-stationary structures: burning does not occur over the whole surface, but it proceeds in the form of separate cells that periodically appear on the burning surface, move along it and disappear.
The images of multi-flame structures above the burning surface of composite solid propellants at 1 atm pressure (11 000 frames/s) are presented at figure 2 [14].

Figure 2. Solid propellant pellet (left) and burning surfaces of pellets containing sieved spherical, flake, 80 nm nAl, Al/PTFE 90/10 wt.%, and Al/PTFE 70/30 wt.% (right). Pressure is 0.1 MPa and all photos were taken with the same exposure settings [14].

The image of multi-flame structures above the burning surface of gray aluminized rocket propellant are presented at figure 3.

Figure 3. Gray aluminized rocket propellant burning in slow motion. Filmed at UIC with the AIAA Rocket Team on February 26, 2018

More than 50 years ago, by numerous experiments begun by Zeldovich Ya.B. had been established the excitation of regular spatial and time structure at stationary propagation of real processes of combustion and detonation explosion, [15]. These micro- and nano- scale structures play a role of micro-scale oscillatory networks in the EM reactionary zones. However, such composite systems cannot be understood, analyzing their parts separately. As was suggested by Novozhilov B.V., the EM burning surface represents the self-excited oscillatory system with infinite number of freedom degrees [16].

In 1951 Zhukov B.P. has shown, that at the EM burning on the boundary between of solid and gas phases there is a liquid-viscous layer (LVL) [17].

Later, the existence of a melt layer was proposed by several researchers (Beckstead and Hightower (1967), [18]), (Tanaka and Beckstead (1996) [19]), (Jeppson and Beckstead (1998) 20]). The micro- and nano- scale oscillatory networks of the EM reactionary zones is associated with both the fractal and self-organized wave patterns formation.
The wave pattern formation phenomena in the EM reactionary zones is programmed by interaction of several competing mechanisms: by excitation of the cellular structures and structurization of the LVL by system of acoustic waves propagating in the combustion chamber (the acoustic-driven excitation); by thermo-electric convection excitation in the EM LVL; by electro-magnetic-driven excitation and by self-synchronization of the self-excited oscillatory cells. In the most of cases, the wave pattern formation is a result of self-organizing of the reactionary zones.

Pattern formation are fascinating phenomena commonly observed in diverse types of biological, chemical, and physical systems, including the area of micro-scale combustion. These phenomena are often responsible for the occurrence of coherent structures found in nature, such as recirculation cells and spot arrangements and their understanding and control can have important implications in technology.

The wave pattern formation from instability is very well known as a general natural phenomenon, and it has been intensively studied in various areas of basic and applied science.

In physics, the patterning behavior can be found in different areas of material processing, such as ion-beam sputtering, thin film deposition, or as a result of femtosecond pulse laser ablation. Understanding of the physical background in the patterning behavior must include the study of mechanisms how some small effects can govern the dynamics of pattern formation. That is the great scientific challenge. In the late 18th century, German physicist Chladni demonstrated the organizing power of sound and vibration in a visually striking manner. In the 1950s the study of wave phenomena was continued by Swiss scientist and anthroposophist Hans Jenny, who named the research field as “Cymatics”, (“kyma” is the Greek word for wave) [21]. Under this term, he summarized all phenomena which appear when tone and sound meet the substance. The sound is both a wave and a geometric pattern at the same time.

Hans Jenny, too, found that higher frequencies produced more complex shapes. As the frequency rises, the dissolution of one pattern may be followed by a short chaotic phase before a new, more intricate, stable structure emerges. If the amplitude is increased, the motions become all the more rapid and turbulent, sometimes producing small eruptions. The shapes, figures and patterns of motion that appeared proved to be primarily a function of frequency, amplitude, and the inherent characteristics of the various materials.

An interesting detail in Jenny’s investigations into sound forms in fluids and gases is that if you first produce a disturbance in a fluid, gas or in a flame, then it becomes sensitive to the influence of sound.

The EM reactionary zones is excellent object to observe the Cymatics phenomena. In accordance with our concept, the excitation of the micro-scale cells on the EM burning surface are not connected with the EM structure but programmed by Cymatics phenomena.

The acoustic-driven excitation of wave pattern formation can be understood within framework of universal laws of Cymatics.

We suggest the new concept, based on universal laws of Cymatics and Unified Template (Mereon Matrix) approach of the self-organized wave patterns excitation phenomenon in the solid propellant reactionary zones. The Mereon Matrix is a 3-dimensional template of a dynamic geometric process [22, 23]. The structure of material systems is formed on the basis of the universal template, the form of which is defined by presence of vibrations in the system. Connection between shape and vibration determined through the Mereon Matrix. In particular, the self-organized wave patterns excitation occurs at excited-state of the solid propellant reactionary zones. The excited-state of the reactionary zones can be described and programmed in accordance with the Cymatics laws.

The system of external acoustic waves and electro-magnetic fields is capable to initiate structuring of the micro- and nano- scale oscillatory networks in the EM reactionary zones.

Study of various model experimental systems that simulate the micro- and nano- scale oscillatory networks in the EM reactionary zones opens surprising possibilities for fundamental understanding of the micro-scale combustion mechanisms.
3. Model experimental systems for study of the wave pattern formation phenomena

The EM LVL can be considered as a medium sensitive to the influence of electro-magnetic fields and acoustic waves, where the self-organized wave patterns formation occurs.

Most visually this phenomenon can be observed in the LVL of the end-burning SP charges. One of primary sources of acoustic waves are the networks of the micro- and nano- scale oscillating structures, excited by a thermo-electric convection, that radiates the acoustic energy into the gas phase. The hydrodynamic instability of micro-scale vortex structures in the combustion products flow also is a source of the acoustic energy. Zone of the gas-phase reactions also is a source of acoustic waves which interacts with the LVL on the burning surface.

In accordance with our hypothesis, the system of acoustic waves is capable to initiate structuring of the micro- and nano- scale oscillatory networks in the EM reactionary zones. Under the influence of the system of acoustic waves the random 3-D micro- and nano- scale structures can turns into the harmonic self-organized wave patterns.

The example of visualization of self-organized wave patterns formed by the micro-size condensed particles at combustion in the eight-beam channel of a cylindrical SP charge in an acoustic field with frequency of tangential oscillations (the frequency is 9–11 kHz, the amplitude is 1 MPa) is shown in figure 4 [24, 25].

![Figure 4. Visualization of coherent distribution of the micro-size condensed particles formed at combustion of the solid propellant in an acoustic field at tangential oscillations: High-speed recording with 2500 frames per minute, [24, 25].](image)

High-speed recording with 2500 frames per minute. On the figure: 1 - is the eight-beam internal channel of the SP cylindrical charge; 2 - is the high-temperature combustion products; 3 - is the micro-size condensed particles (d = 5 mkm). The micro-size condensed particles in the combustion products allows to make physically visible the sound wave patterns. Sound frequencies in this experiment cause random particles to assume geometric wave patterns.

The phenomena of self-organized wave patterns excitation also are observed at burning of the paraffin-based propellants in hybrid rocket systems. The cutaway views of the hybrid rocket fuel grain (50% HTPB + 50% Paraffin) are shown in figure 5 [26]. Patterned elements appear as lattice-like arrays, accompanied by vortex formations.

Here again we are confronted by an exceptionally complex series of events: unstable currents, turbulence and vortex formations on the one hand, and an self-organized pattern on the other; both representing the effect of vibration on the stream of gas.

The system of interacting flames can be considered as a model experimental system for many practical applications. For instance, for study of acoustic-driven excitation of the wave pattern formation. The better understanding of self-organizing and self-synchronization of the array of interacting flames can give us the possibility for control of combustion instabilities in the SPS.
The experimental studying of thermal and electrical structure of the diffusive flames has shown that they can be used for modeling a flames of the composite solid rocket propellants [27].

Figure 5. The phenomenon of self-organized wave patterns formation are observed at burning of the paraffin-based propellants in hybrid rocket systems. Self-organized wave patterns on the surface of hybrid rocket fuel grain after firing tests. The cutaway views of the hybrid rocket fuel grain (50% HTPB+50% Paraffin) [26].

The 2D Rubens’ pyro board can be considered as a model experimental system for demonstration of the micro-flames self-synchronization phenomenon and interaction of the micro- and nano- scale oscillatory networks with the EM reactionary zones. Sound-sensitive flames are known to become sensitized only by disturbance, i.e. by turbulence in the stream of gas (Zickendraht, 1932). A turbulent medium is sensitive to vibration; acoustic waves can make their influence felt in a turbulent medium. Hence the turbulent gas reacts to acoustic irradiation. A Rubens’ tube, also known as a standing wave flame tube, is a tool for demonstrating standing acoustic waves (see figure 6).

Figure 6. 2D Rubens’ tube “Pyro Board” that translates acoustic waves into dancing flames, revealing the hidden waves in sound.
Invented by German physicist Heinrich Rubens in 1905, the Rubens’ tube graphically shows the relationship between sound waves and sound pressure, as a primitive oscilloscope. The “Pyro Board” takes the Rubens’ tube to the next level, by visualizing audio across a plane, instead of just in a line. Small flames of gas burned through these holes and thermodynamic patterns were made visible by this set-up. The pressure variations due to the sound waves affect the flow rate of flammable gas from the holes in the Pyro Board and therefore affect the height and color of flames. The Pyro Board itself is a 2D plane that comprises of 2.500 Bunsen burners (see figure 6).

The system of small gas burners can provides a system of controllable flames. This is one of the model experimental systems demonstrating a capability of programming of the EM reactionary zones by external acoustic waves.

Recent experimental data on SP combustion demonstrates considerable influence of acoustic waves onto micro- and nano- scale oscillatory networks of the reactionary zones [28].

4. Electro-magnetic self-organizing in the reactionary zones
The idea of using electro-magnetic fields to manipulate SP burning rates is not new. In fact, this concept was proposed at least as far back as the 1960’s. In general, the application of electro-magnetic fields to a combusting SP has shown to increase the burning rate of the propellant, and even under certain conditions can decrease the burning rate as well [29].

The effects, which an electro-magnetic field exerts on flames, have been observed and reported in the literature for a long time. Flames interact with external electric and magnetic fields, which can be used to monitor, manipulate, and enhance the processes that make up combustion through a variety of physical and chemical mechanisms. Even fields that are too weak to influence combustion directly can cause significant hydrodynamic flows - so-called electric or ionic winds - through the collisional transfer of momentum from accelerated charged species to the neutral gas. The electric field interacts with the charged particles in the flame - the electrons, ions and soot particles - and this collective motion of the charges in the electric field can lead to movement of the gas within the flame.

In accordance with recent experimental results, the electro-magnetic phenomena play a key role both in the LVL and in the flame zone of the burning EM. At heating from above, in the EM thin LVL the thermo-electric convection excitation occur, which induces cellular movement and formation of the synergetic micro- and nano- scale structures [2]. The electric field micro- and nano- scale structures in the LVL gives the program for formation of the cellular-pulsating micro- and nano- scale structures in the heated-up LVL, on the burning surface and for excitation of periodic toroidal vortex micro-scale structures over the burning surface. In conditions of the burning wave, where the temperature in the condensed phase increased by exponential law, the thin reactionary LVL can be considered as the molten mass with ionic properties.

In accordance with experimental researches connected with studying of electrical structure of the flame [27, 30], the flame of composite SP and hybrid rocket propellants possesses own electric field of a complex structure with localization of zones of positive and negative electric charges.

Presence of distributed electric charge in the flame allows to manipulate by shape of the flame by means of external electric field, and, hence, by distribution of the heat sources, by the heat flow into the condensed phase and, at last, by burning rate.

Electro-magnetic self-organizing in the EM reactionary zones is induced under the influence of a thermo-electric field in the LVL and as a result of separation of electrical charges because of distinction in diffusion coefficients and mobility of charged particles in the flame.

Also, in the model experimental system the excitation of the wave patterns in the liquid layer in conditions of external electrostatic field was observed [31, 32]. The experiments revealed an anomalous behaviour of the liquid layer combustion during the phase transition in the conditions of presence of an external lateral electrostatic field. The phase transition in these conditions, at a certain field strength, follows the explosive boiling mode. Changing the evaporation mode to explosive mode boiling-up dramatically increases the burning rate.
It has been shown experimentally that when a constant current electric discharge is applied to the combustion zone, an internal negative feedback suppresses vortex formation in the thermal boundary layer and the pressure oscillations at all harmonics, simultaneously [33].

On the other hand, when a constant voltage discharge is applied, excitation and amplification of unstable combustion are observed. The estimates show that the electrical energy required to suppress the unstable burning of a singing flame by this method is an order of magnitude lower than the chemical energy release [33].

In addition, the experiments on controlling combustion stability in more thermally stressed combustion chambers, for example, in a model of a ramjet engine, have shown that the required electrical energy is two or more orders lower. At stabilization of the discharge by high-frequency current, the degree of turbulence decreases, and at stabilization of discharge by voltage the degree of turbulence is increased.

Use of controlled electric discharge allows to slow or accelerate motion of a wave of combustion front. This method for controlling combustion instability is realized through an "internal" feed-back. In this case, the combustion itself regulates the controlling discharge without using the sensors, amplifiers, phase inversion devices, etc., required for external feedback. This sort of feedback, either negative or positive, is the fastest and is essentially instantaneous. The control technique described here was tested on a singing flame with premixed propane-air mixtures [33].

If the electric discharge is imposed on the combustion zone, then the total rate of a heat release consist of rate of heat release provided by combustion and rate of Joule heat release in the discharge. The pressure oscillations are suppressed through an additional parametric negative feed-back. This means that the discharge does not affect the pressure oscillations directly, but serves only as the cause of changes in the parameter for the self-oscillatory process, which is coupled to the pressure oscillations through a definite chain.

5. The resonance spectrum of the micro- and nano-scale structures
In the EM reactionary zones can be observed a unique set of holograms: image, acoustic, electromagnetic and thermal. These holograms can be used as equivalents for excitation of the resonance spectrums of the predetermined set of molecules or micro- and nano-scale structures in the reactionary zones.

According to our hypothesis, each EM has a unique set of holograms of the reactionary zones in available specific frequency bands, because the holography is applicable to the waves of any nature [34]. For example, under the influence of the system of electro-magnetic fields or/and acoustic waves the random 3-D micro- and nano-scale structures can turns into astonishing forms. Such oscillatory structures can form the self-organized wave patterns, in particular, the Chladni patterns. Self-organized wave patterns formation in the EM reactionary zones can be considered as visualization of the unique set of holograms of the EM reactionary zones.

In accordance with theoretical and computational studies [35, 36], based on the novel physical and mathematical model of non-equilibrium chemical processes involving vibrationally and electronically exited molecules have shown that selective excitation of reacting species by laser radiation results in a considerable reduction of self-ignition temperature, decrease of induction and combustion times, and initiates detonation in supersonic flow at relatively low radiation energy inputted into the mixture. These effects are due to production of the novel channels of high reactive radicals formation and enhancement of chain mechanism of combustion and are not associated with the thermal action of absorbed radiation.

The burning of the most combustible mixtures occurs through the mechanism of chain-branching reactions. Therefore, in order to enhance the combustion, one needs to excite those molecules that can produce in the course of chemical reactions the highly reactive atoms and radicals. One efficient approach to exciting the vibrational or electronic states of target molecules is exposure of the mixture to resonance laser radiation. Experimental data show that molecules excited even to the lowest vibrational or electronic states react 10-100 times faster than unexcited ones. Excitation of the target
molecules in the reactionary zones gives the possibility for manipulation by the scale and 3-D localization of the induction and energy-releasing areas and, accordingly, allows control inter-scale interaction in the SPS.

Excitation of the resonance spectrums of the predetermined set of molecules in the reactionary zones are capable to induce self-organizing of the 3-D micro- and nano- scale structures and to activate and to deactivate different physical properties: electromagnetic, electric conductivity, sizes of the micro- and nano- scale structures etc. Also, such excitation of the resonance spectrums can be used for reduction of the reactionary zones sizes and for suppression of the combustion instability. The additional technical result is connected with increase of the energy-release rate in the reactionary zones. In particular, programming of the space structure of the reactionary zones, i.e. creation of spatially-local zones with various rates of reactions and energy release is possible.

The acoustic or electromagnetic holograms can be used for excitation of the self-organized wave patterns in the EM LVL and for programmed transfer of the quantum information into the reactionary zones for excitation of the resonance spectrums of the predetermined set of molecules.

6. Self-organizing and self-synchronization of self-excited oscillators networks
Synchronization of a large number of oscillators is a well-known form of collective behaviour [37]. These phenomena are universal. Oscillators with similar frequencies can obviously synchronize when phase-minimizing coupling acts between them.

The micro- and nano- scale structures of the EM reactionary zones can be classified as the synergetic objects. In the EM reactionary zones exists necessary conditions for realization of the phenomenon of self-synchronization. First of all this is a set of similar micro- and nano- scale oscillatory structures, which have an identical information-algorithmic condition and being in the conditions supposing fast information exchange between them. Fluctuating micro- and nano- scale structures also are generators of the acoustic waves and electro-magnetic radiation. One of examples of collective interaction and self-synchronization of the micro- and nano- scale structures in the EM reactionary zones are the process of excitation of the burning cells in the reactionary zones of strobos, [38]. The simple model nonlinear oscillatory experimental system containing a set of paraffin candles can be used for experimental studying of the phenomenon of synchronization of the torch micro-structures over the EM burning surface [4].

The experimental studying of thermal and electrical structure of the diffusive flames, which models a flame of the composite SP, has shown possibility of control of the burning rate of propellant by change of heat flux to the burning surface by superimposition of a dilatational electric field on the flame, [30]. At superimposition of the external electric field on the flame, occurs change of the shape and the height of the flame. It is caused by presence of the distributed electrical charge in a flame. Together with it there is a change of a position of radiants of thermal emission in the flame, a change of heat flow on the burning surface and burning rate. The EM reactionary zones can be considered as excitable systems. Actually, self-synchronization of the micro- and nano- scale structures provides the mechanism of interactions between micro- and macro- scale levels in the EM reactionary zones.

According to our hypothesis, self-synchronization of the micro- and nano- scale oscillatory systems in the reactionary zones occurs through both the acoustic waves and electro-magnetic fields interaction. The phenomenon of self-synchronization of the micro- and nano- scale oscillatory systems in the reactionary zones was considered in paper [39]. The acoustic waves and electro-magnetic fields are major factors in the reactionary zones that are capable to initiate the self-synchronization phenomenon. Simultaneous interaction of these two factors in the reactionary zones will induce phenomenon of synergy and will intensify self-synchronization phenomenon. Such interaction of the electric charges and electro-magnetic fields changes the space localization of the reaction zone and the sources of heat release in the burning zone.

Self-organizing of the EM reactionary zones is a key link in the control methods by combustion regime. The new possibilities for effective control by ignition and combustion processes opens in
connection with possibility of initiation of self-organizing of the reactionary zone by use of the electric fields, acoustic waves and special kind of electric discharges.

Self-organizing of the EM reactionary zones is essentially new level of self-organizing which is determined by achievement of critical spacial concentration of the micro- and nano-scale structures - by a bifurcation point.

Self-synchronization of oscillations of the torch micro-structures under the influence of external action can excite combustion instabilities in the combustion chambers of the SPS. In the greatest degree, the effects of self-synchronization will be observed at low pressure levels, when the micro- and nano-scale structures in the reactionary zone have the maximum size. At reduced pressure levels the majority of anomalies of ignition and combustion are observed.

Self-synchronization of the micro- and nano-scale structures are capable to induce changes of distribution of heat flows and to induce the combustion anomalies.

In the middle of the nineteenth century, in his famous treatise “The Theory of Sound”, Lord Rayleigh described an interesting phenomenon of synchronization in acoustical systems [37]. Rayleigh observed not only mutual synchronization when two distinct but similar pipes begin to sound in unison, but also the related effect of oscillation death, when the coupling results in suppression of oscillations of interacting systems. Diffusive coupling is capable of suppressing intrinsic oscillations due to the manifestation of the phenomena of amplitude and oscillation deaths [40, 41]. The phenomenon of oscillation death (OD) refers to situation, where the coupled oscillator system cease oscillation and exhibit a stationary state [40]. Amplitude death (AD) is one of the intriguing phenomena that occurs in coupled oscillators when they interact in such a way as to suppress each others oscillations and collectively go to the stable fixed point that was unstable otherwise. For instance, in the result of interaction of the networks of self-excited oscillators in the EM reactionary zones in self-synchronization mode the phenomenon of quenching or death of oscillations can be observed. Then, the wave of quenching or death of oscillations can propagate on all burning surface.

7. Model experimental systems with plasma actuators as a force field emitters

In recent years, the development of devices known as plasma actuators has advanced the promise of controlling flows in new ways. Plasma actuators are one of the most promising technologies to manipulate a turbulent jet with strong potential benefits in mixing efficiency for combustion, propulsion efficiency and noise reduction. The plasma actuators are small devices that use high electric potential to accelerate portion of the flow field [42]. Three main types have already been used for turbulent jets, Localised Arc-Filament Plasma Actuators (LAFPA), Plasma Synthetic Jet (PSJ) actuators and more conventional Dielectric Barrier Discharge (DBD) plasma actuators, as seen in figure 7 [42].

![Figure 7. Simplified schematics for LAFPA, PSJ and DBD plasma actuators](image)

The effect of the plasma actuators can easily be seen with ejections of pairs of elongated streamwise vortical structures generated between two plasma actuators. The plasma actuators are able to strongly modify the flow field downstream of the nozzle with more or less the same flow rate as the non-controlled cases.
The plasma actuators also are used to control instability waves in the shear layer of a turbulent air jet [43]. The actuator model for artificial instability waves (AIW) control was developed using a concept of the dual actuator. The working surfaces of the surface barrier corona actuator consist of two thin dielectric discs. The high-voltage electrodes (corona needles) are placed on each disc (figure 8).

**Figure 8.** (a) Scheme of dual disc surface barrier corona discharge-based plasma actuator and (b) photo of the sectioned surface barrier corona discharge (top view). (1) Quartz disc (external diameter 170 mm, inner diameter 60 mm, thickness 3.5 mm) (2) 36 needle electrodes (3) common high-voltage electrode (4) grounded electrode in the form of aluminum foil glued to the underside surface of the disc [43].

The actuator generates an axisymmetric radially convergent gas flow. This actuator allows the generating of intermittent (or pulsing) gas jet with the modulation frequency in the range of \( f = 0.5\text{–}5.0 \text{ kHz} \). The outlet jet velocity \( V \) can be varied up to 14 m s\(^{-1}\). In the case of the dual disc actuator, the surface barrier corona discharge was excited by a sinusoidal voltage with a frequency of 100 kHz. Power input to the discharge varied during the experiment in the 200-600 W range. Modulation of the velocity of gas flow following from the dual actuator was carried out by modulation of the discharge voltage: an AC sinusoidal voltage was applied to the discharge electrodes in the form of pulse trains with variable duration and duty cycle.

In particular, research [43] demonstrated that the control of the artificial instability waves (AIW) via external acoustic excitation is feasible, i.e. it was experimentally shown that a time-harmonic instability wave can be suppressed by an external acoustic wave with the properly chosen amplitude and phase. Plasma actuator excitation leads to instability wave/vortex ring formation in the jet shear layer for the three elaborated types of plasma actuators. The power input values for each actuator which generated AIW with equal amplitudes (\( \sim 12 \text{ m s}^{-1} \)) are within the range of (180-300) W.

**8. Plasma arc emitters and the electro-acoustic coupling mechanism**

Sound emission using an ionised medium has been the subject of research since the beginning of the 20th century. A plasma arc emitter is a device that uses ionized gas as the driving source of acoustic waves production. Similar to how lightning produces sound, or even a small static shock, a plasma emitter uses a modulating electric arc between two electrodes to produce acoustic waves.
The base for plasma arc emitters, also known as ionophones, was the invention of William Duddeles back in 1900. The technique is an evolution of William Duddell’s “singing arc” of 1900, and an innovation related to ion thruster spacecraft propulsion. William Duddeles found that by varying the voltage to the arc, it changed the sound that was produced. Much later a fellow by the name of Siegfried Klein got involved and tuned it by putting the arc in a small quartz tube. Coupling this to a horn, he was able to produce a speaker and a microphone.

The mechanism involves modulation at an audio frequency of an electrically sustained plasma discharge. In a similar effect to lightning, the charged particles in the plasma respond to the varying energy input. With this comes gas heating, molecular excitation, light emission from relaxation of excited molecular states and acoustic emission resulting from thermal expansion within, and external to, the discharge volume.

The electro-acoustic coupling mechanism [44] makes a plasma generate sound. An electro-acoustic coupling mechanism is most familiar in the form of a hi-fi loudspeaker where audio frequency current through a coil oscillates a cone attached to a magnet. The oscillations cause displacement of the air at the cone with the resulting pressure variations propagating away from the source as sound. The same effect can be achieved if the mechanical system is replaced with an ionised gas. The charged particles within the plasma readily respond to electrical modulation and, through a process of energy transfer to the surrounding gas molecules via a number of mechanisms within the plasma, pressure waves can be generated.

In the controlled ionized channel occurs the energy transfer mechanism between the current and the acoustic emission. The effect takes advantage of two unique principles.

Firstly, ionization of gases causes their electrical resistance to drop significantly, making them extremely efficient conductors, which allows them to vibrate sympathetically with magnetic fields. Secondly, the involved plasma, itself a field of ions, has a relatively negligible mass. Thus as current frequency varies, more-resistant combustion products remains mechanically coupled with and is driven by vibration of the more conductive and essentially massless plasma, radiating a potentially ideal reproduction of the acoustic emission.

There are two acknowledged mechanisms by which a plasma can be made to produce acoustic waves. The first relies on the transfer of momentum from charged particles to neutral gas molecules during collisions between the two and is commonly referred to as a forcing mechanism. In the second mechanism, commonly known as the thermal mechanism, the pressure fluctuations are caused by expansion within an ionised column. The rapid heating in the ionised column results in thermal expansion, where the dimensions of the plasma expand and contract as the charged species respond to the applied modulating electric field. This leads to pressure variations within and external to the column. For this mechanism, adiabatic conditions within the column are required as the rate of energy transfer relative to the conduction of heat out of the system is critical in establishing pressure variations.

There are several advantages to using direct electro-acoustic coupling via a plasma. Due to its negligible mass, the plasma responds quickly to changing electric fields and is able to reproduce a desired broadband response while faithfully reproducing an input electrical signal.

Under modulation the plasma behaves as a uniform acoustic emitter with the level of the acoustic wave being dependent on the discharge size.

The charged particles within the plasma readily respond to electrical modulation and, through a process of energy transfer to the surrounding gas molecules via a number of mechanisms within the plasma, pressure waves can be generated.

Plasma emitter can vary the size of a plasma glow discharge, corona discharge or electric arc which then acts as a massless radiating element.

The model experimental system with using of the axially symmetric ring-shaped gas discharges for excitation of the self-organized wave patterns in the reactionary zones presented on the figure 9 [45].
The example of self-organized wave patterns excitation in the reactionary zone by the ring-shaped electric discharge is shown in figure 10 [38].

This is a typical shadow photographs taken in the direction orthogonal to the plane of the ring-shaped electric discharge when operating with a methane-oxygen mixture (CH\textsubscript{4} : O\textsubscript{2}) and oxygen (O\textsubscript{2}). The delay time with respect to the discharger trigger pulse is indicated in the figure. The gas-dynamic processes of the ring discharge in a methane-oxygen medium are more intricate than those in chemically inactive gases.

The distinctive feature of this discharge is the generation of a second wave of strong gas-dynamic perturbations, which is also converging towards the axis. The induction times at the initiation of combustion by a ring discharge turn out to be much shorter in comparison with linear gliding discharges, microwave discharges at plane targets and laser sparks with nearly the same energy released [45].
Complexity and peculiarity of this discharge action on a flammable gases flow consists in excitation on a periphery combustion wave with concurrent generation of convergent to the axis cumulative shock wave transforming near the axis into a detonation one.

The ring-shaped discharge actually does make plasma functional force field, accompanied by the acoustic emission.

9. New concept and technology for the reactionary zones excited-state programming
As has been shown above, control by self-organized wave pattern excitation and by the micro- and nano- scale oscillatory networks is one of the effective ways to access to the properties of the SP reactionary zones.

The innovative aspect of this concept & technology is the plasma-acoustic coupling mechanism that transforms the input electrical energy into the directed acoustic energy.

Use of the plasma-acoustic coupling mechanism for the self-organized wave pattern excitation in the reactionary zones is one of the advanced ways to access to the properties of the reactionary zones: the scale and localization of the induction and energy-releasing areas.

The plasma glow discharge, corona discharge or electric arc which then acts as a massless radiating element. It creates the compression waves in the gas. At the same time, the plasma arcs have zero weight.

Generation of the plasma arc within a magnetic field perpendicular to its current path results in a Lorentz force on the charged particles, causing the arc to sweep about the center of the coax, forming a plasma disc.

The technology of plasma arc emitters, modulated by acoustic frequencies, can provide manipulation by self-organization and by self-synchronization of the micro- and nano- scale oscillatory networks and self-organized wave pattern formation in the EM reactionary zones. Also controlling of self-organizing and self-synchronization of the micro- and nano- scale oscillatory networks can be used for suppression of the anomalous intra-chamber oscillating processes.

The oscillating plasma disc will constantly exists over the burning surface. For instance, the plasma arc force field emitter can be installed over the burning surface of the solid propellant end-burning charge with using of the special design of the electrode system.

The electrode control system can be manufactured as a set of electric-conductive rings consistently installed over the internal surface of the propulsion system casing (figure 11).

![Figure 11. Design of the Throttling Solid Propellant Propulsion Systems with end-burning charge](image)

The concept includes integration of the propellant reactionary zones both into the control system by combustion mode, and into the general control system.

Programmed acoustic emission from the oscillated plasma arc disc into the reactionary zones opens possibilities for manipulating by the networks of the micro- and nano- structures.

Application of different acoustic frequencies, emitted by the plasma emitter, will activate specific properties of the reactionary zones and will change the localization and properties of the reactionary zones. Also such emission can excite the self-organizing of the SP reactionary zones.
For optimum control by excited-state of the reactionary zones, we suggest to use a combination of several modes and parameters of formation of the ring-shaped discharges. Different types of discharges and plasmas can be obtained depending on the applied voltage and the discharge current. It has been shown experimentally that when a constant current electric discharge is applied to the combustion zone, an internal negative feedback suppresses vortex formation in the thermal boundary layer and the pressure oscillations at all harmonics, simultaneously. On the other hand, when a constant voltage discharge is applied, excitation and amplification of unstable combustion are observed. The estimates show that the electrical energy required to suppress the unstable burning of a singing flame by this method is an order of magnitude lower than the chemical energy release. At stabilization of the discharge by high-frequency current, the degree of turbulence decreases, and at stabilization of discharge by voltage the degree of turbulence is increased. Use of controlled electric discharge allows to slow or accelerate motion of a wave of combustion front. This method for controlling combustion instability is realized through an "internal" feedback.

Let’s observe the experimental confirmation of the reactionary zones programming by the external acoustic waves. The combustion response of the propellant sample to the acoustic wave excitation demonstrated on the figure 12 [28].

![Figure 12. Combustion response of the propellant sample to the acoustic wave excitation (mean pressure 1 MPa, time interval 1250 ms) [28].](image)

The qualitative and quantitative analysis of these experimental data [28] revealed that the acoustic wave strongly affects the combustion product flow, induced modifications on the flame structure and position, the burning surface profile, the burning rate, the flow velocity of the aluminum particles in the combustion products, and the distribution of the agglomerates. The hot product particles follow perfectly the displacement imposed by the acoustic wave, their motion enhances the molecular mixing. Therefore, the flame stand-off distance is decreased and the heat feedback to the solid phase is increased.

In accordance with the experimental data, under the influence of an electric current the solid propellant are capable for stable burning at the atmospheric pressure. Supporting of electrical
conductivity of the LVL in the conditions of low pressures can be used for multi-ignition of the propellant without use of the ignition system. Combination of possibility of extinguishing in the electric field with supporting of electric conductivity of the LVL and with use of electric discharges opens possibility for multi-ignition of the propellant.

Such method of control by the micro- and nano- scale oscillatory networks in the reactionary zones can be organized with assistance of the neural network-based system.

Neural network-based system allows to process, analyze and use the Cymatics information - a set of image, acoustic, electro-magnetic and thermal hologrammes that are registered online in the EM reactionary zones. Through online retaining, the neural network-based system can provide precise optimization of the intra-chamber processes and thrust by accommodating of the reactionary zones self-organizing due to flight program and improving operating flexibility. The main advantages of the proposed approach consisted in the natural ability of neural networks in modeling nonlinear dynamics in a fast and simple way and in the possibility to address the process to be modeled as an input-output black box, with little or no mathematical information on the system.

10. Conclusions
Smart control by excited-state of the reactionary zones and by self-organized wave patterns excitation with use of the plasma-acoustic coupling mechanism is one of the promising ways to access to the properties of the reactionary zones: the scale and localization of the induction and energy-releasing areas. Application of different acoustic frequencies, emitted by the plasma arc emitters, can change the localization and properties of the reactionary zones. Application of the plasma arc emitters in the reactionary zones is opening the new ways for inertial-free control by the structure and properties of the reactionary zones with minimum expenses of energy. Suggested concept for manipulating by self-organized wave patterns and by oscillatory networks of the micro- and nano-scale structures in the reactionary zones with using of the plasma force field emitters and new generation of the electrically activated solid propellants is opening the door for completely new ways for producing extremely small thrust impulses for the extra-precise attitude control for the deep-space-capable small satellites.

This complex work is partly on-going now, and the results obtained will be presented in our future publications.

Acknowledgments
This research was supported by the Western-Caucasus Research Center.

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