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Numerical study of the contactlessly fed vibrators system destined for at surface airflow heating

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For control of boundary layer flows can be used the line of periodically located spots of energy addition near overflowing surface. One of methods of the energy addition is gas discharges initiated by electromagnetic system placed under surface and fed by microwave radiation. The problems of designing and electromagnetic tuning of the system used in aerodynamic experiment are described.

Nomenclature

E	=	amplitude of electric field
E_0	=	amplitude of electric field of microwave radiation
E_{cr}	=	critical value of electric field amplitude
c	=	light velocity
ω, λ	=	microwave radiation circular frequency and wave length
k	=	$2\pi/\lambda$ - wave number
e, m	=	electric charge and mass of electron
E_{DCcr}	=	DC critical electric field

I. Introduction

One of the possible applications of microwave (MW) technology is a structured heating of airflow near overflowed surface by located on it system of electrically conductive elements excited by electromagnetic MW radiation. Such possibility is being stood in experiment[1,2], which scheme is presented on Fig.1. In that experiment the plasma discharge feed by MW current inducted in gaps of loop-shaped metal vibrators placed in beam of MW radiation. Heat release in discharges generates the periodical structure of vortexes, influencing on characteristics of overflow. The experiment is being performed successfully.

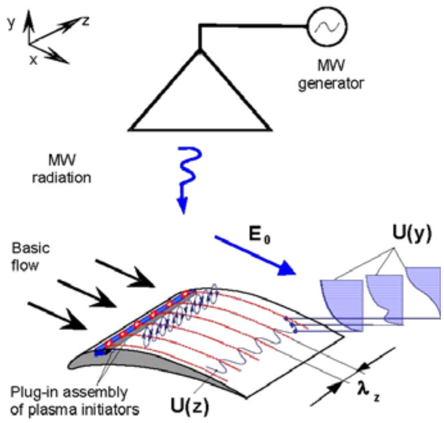

Figure 1. Scheme of aerodynamic experiment on boundary layer control

But the same idea of vortex generation can be realized by means of use of vibrators loaded by plasma discharge. This variant has a definite advantage.

Simultaneously a row of difficulties is arising, which demand its detail investigation. The paper is devoted to numerical study of electromagnetic tuning of vibrator system placed in a field of MW radiation. Geometrical parameters of vibrators and period of their dislocation in system are varied for the determining conditions of maximum efficiency and homogenous distribution of heating power in discharges.

From earlier investigations, described in Ref.3 and more detail in Ref.[4], the typical values of optimal parameters, particularly, the discharge conductivity, are known. Usually, for maximal absorption efficiency the electric conductivity individual discharge cannel must have a value corresponding to its equality to radiation resistance.

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II. Problems of electromagnetic tuning of resonant system loaded by discharges

For experimental check of idea of influence on separated streams by generation of periodic vortical structure by means of surface allocation of thermal energy in a stream electrode microwave (MW) discharge raised above a streamline surface has been chosen. The periodic structure of local MW discharges should create necessary effect.

In the chosen type of the initiator, described in Ref.[5,6] and successfully used in experiment, the local discharges arise between the ends of the wire electrodynamic vibrator of the resonant length turned into not closed ring and fed remotely by external MW radiation (Fig.1). Advantages of application of electrode discharges is not only an opportunity of their wireless feed by means of MW radiations, but realization of heating of gas directly in channels of the discharges poorly contacting to a body surface without its inadmissible warming up.

The ring vibrators located coaxially on the set distance from each other with gaps on the common plate, form system of vibrators as it is shown on Fig.2. On Fig.3 and Fig.3 an accommodation of system of initiators in model of a wing is shown.

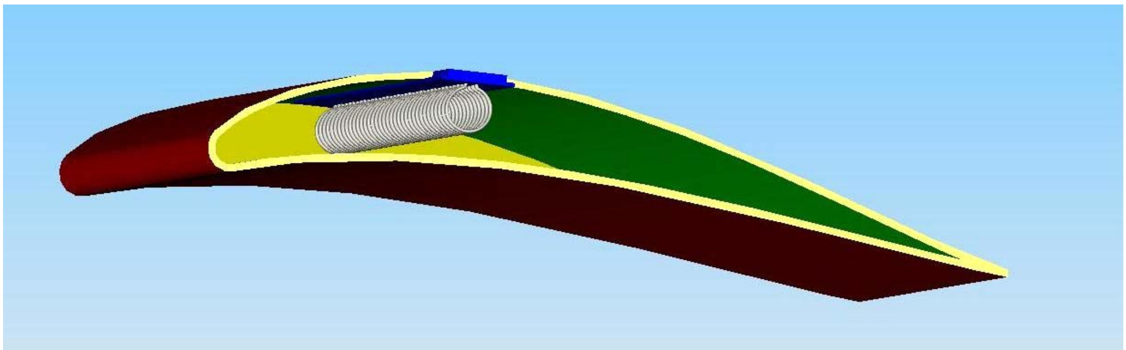


Figure 2. Accommodation of system of initiators in model of a wing used in aerodynamic experiment.

Earlier it has been investigated[5] that a condition of an electrodynamic resonance of the separate ring vibrator is provisional equality of its perimeter to half wavelength of MW radiation. Calculation also has shown, that radiation resistance of the ring vibrator with resonant length is less than radiation resistance of the rectilinear vibrator in several times, falling with reduction of distance between the ends of the vibrator from 75Ohm up to 10Ohm

Therefore good quality of the vibrator, not loaded by discharge, increases from usual values 5-6 up to value 25-30. Accordingly, as have shown both calculations, and experiments, amplitude of an electric field in a gap of the resonant ring vibrator can exceed amplitude of an external field in a place of its location in 250 - 300 times and more. Breakdown of air of atmospheric pressure allows carrying out air breakdown at rather small level of MW radiation.

The system from such 11 ring vibrators located with the period 1sm has been successfully applied in the aerodynamic experiment yielded the first positive results.

However aerodynamic calculations show[2], that for achieving of desirable result, the system with period of 0.5sm is match. Therefore for realization of experiment in full width of wing model in experiment (20 cm) is necessary to have structure of 40 resonant vibrators. Maintenance of required parameters has met the certain difficulties.

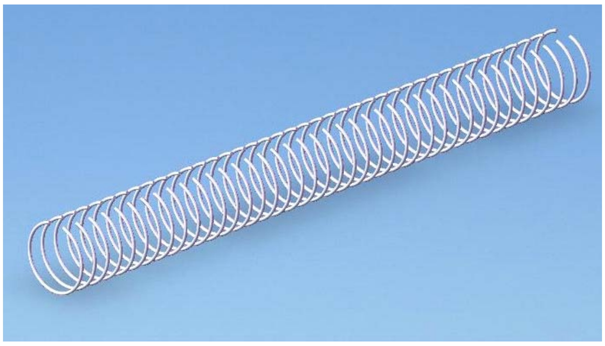


Figure 3. System from 40 ring vibrators, located with period 0.5 cm.

As it was marked above, the system of close located ring vibrators forms the electrodynamic connected allocated system possessing set of electrodynamic resonances, corresponding to various distributions of currents in vibrators. Therefore generally distribution of amplitude of a current in vibrators is non-uniform on system and is determined as geometrical parameters of system and frequency of MW radiation, and Ohm losses, brought by discharges in each vibrator individually. As parameters of the discharge essentially nonlinear depend on the induced current in the vibrator the adjustment of such system is an independent problem which can be subdivided into three sub problems:

- the achieving of sufficient uniformity of excitation at increase in number of vibrators in system and reduction of distance between them,
- the defining of minimum level of MW radiation, providing breakdown of all gaps and maintenance of discharges in a steady mode,
- the defining of necessary generator power for excitation the minimum level in conditions of spent experiment.

At distance between the neighborhood vibrators, smaller their bigger diameter, when electrodynamic connection between vibrators becomes greater of critical value, the amplitude of currents in system starts to be determined by a condition of interference. Number of possible modes in system with discrete resonant elements equals to half of their total number. With growth of number of elements the distance on frequency between the next modes decreases, so small changes of system parameters or frequency of the generator lead to strong redistribution of currents on vibrators. Reception of homogeneous distribution, which corresponds to the lower mode, in a resonant regime is strongly complicated. Excitation in the not resonant regime demands essential increase in power of the generator.

Figure 3 shows the system from 40 ring vibrators, which geometrical parameters is the same that at used in the lead experiment, located with period 0.5 cm. Such system corresponds to the optimum period and length of system for conditions of the experiment. It could be used, but if not noted difficulties.

Electrodynamic calculation of this system (by means of code CST MW SUITE) at excitation by radiation with flat phase front and amplitude 100 V/cm on wavelength 12.33cm has given inadmissible non-uniform distribution of electric field amplitude in gaps (see Fig.6). The 10-th mode (instead of a desirable zero mode) is excited mainly. Distance between modes on frequency so small what to provide option for the desirable mode it is impossible, not exciting the several next modes. Calculations have shown too, that the situation is not easier and in case of system of 20 vibrators with the period 1cm.

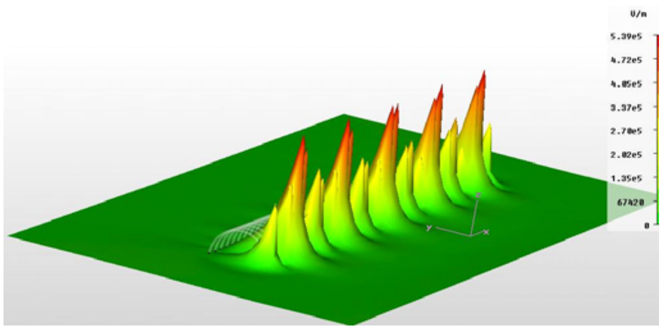


Figure 4. Distribution of electric field amplitude in plane z=0. Number of vibrator – 40, period - 0.5cm

For preservation of idea of resonant excitation of alone lower mode (with a view of minimization of level of MW radiation and providing the necessary homogeneity of currents in all vibrators), development of other type of initiating system is required.

The developed system of discharge excitation represents sequence of N resonant contours strongly connected among themselves. Such sequence forms the allocated resonant system in which excitation of N/2 mode with distribution of the induced currents depending on ordinal number of a contour is possible

$$I \sim \cos\left(m \cdot \pi \cdot \frac{n}{N}\right), n = 0 \div N, m = 0 \div N/2$$

At symmetric excitation that is determined by symmetry of an exciting field, there are modes with even value ***m***. In the developed system the own frequencies of modes are located so close, that at final good quality of contours the exciting a separate mode, not exciting of several next, is impossible. To excite a mode with ***m***=0, corresponding homogeneous distribution of power in gaps, in the used system is possible only by exit for limits of band of resonances of system. It essentially reduces effective cross-section of its interaction with MW radiation and increases requirements to power of the generator.

In future it is supposed to use of a new variant of resonant structure with the rarefied spectrum of mode of own oscillations, at which excitation of a demanded mode m=0 without excitation of the others is possible.

III. The possible way of problem solving

Here we shall plan a probable way of the decision of a problem of resonant excitation of a zero mode in the system of any length providing initiations of discharges with the set period.

In a limiting case of a small step of periodic system of ring vibrators the situation comes nearer to a case of the continuous cylindrical tube, with a longitudinal cut. On Fig.5 the cylindrical tube with a cut for which calculation in the conditions specified above has been lead is shown. Cylinder axis, wave vector and electric field are oriented along x, y and z correspondingly. Length of the cylinder is 20cm, radius is 1cm, and a gap is 0.4cm. Sizes of the tube and wavelength of radiation correspond to conditions of experiment.

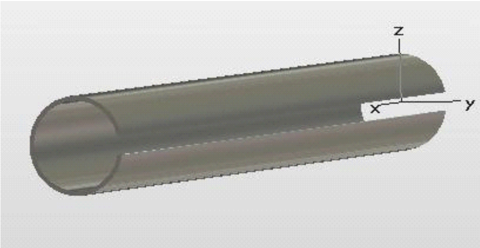


Figure 5. Cylindrical tube with longitudinal cut.

Spatial distribution of electric field amplitude in plane of cut is shown on Fig 6. It is possible to compare with the similar distribution calculated for system of the same length and radius consisting from 40 separated ring vibrators (see Fig.4), received at the same conditions of excitation (an external field 100 V/cm). Unlike system of ring vibrators where distribution of amplitude of a field on gaps of rings is

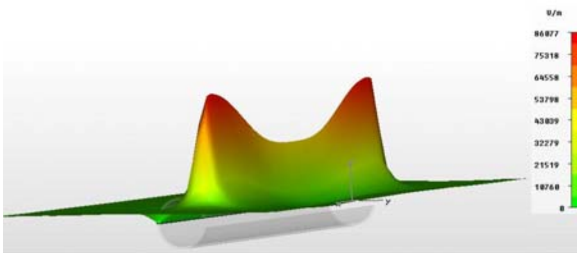


Figure 6. Spatial distribution of electric field amplitude E(x,y) at cut vicinity.

rather non-uniform, distribution of amplitude of an electric field along a cut section of the cylinder is smooth enough. Two lower next modes are excited simultaneously. However the average amplitude is in 3-8 time smaller, than in case of separate ring vibrators. It is no wonder as in a cut of the cylinder there is no aggravation of a field on the sharp endings of vibrators.

For elimination of this lack and maintenance of localness of discharge initiation in the cylinder with a longitudinal cut the transverse cuts was executed with the set period 0.5 cm and set depth equaled to 0.25 of the tube diameter. Appearance of offered initiating system is shown in Fig.7.

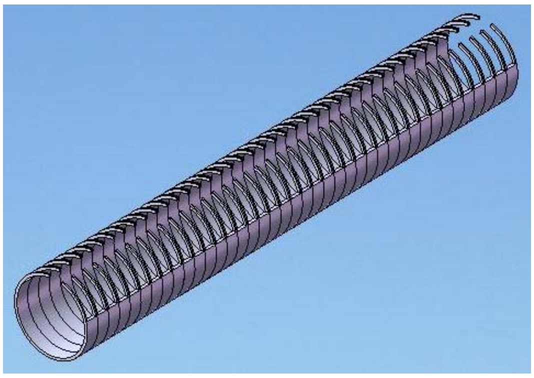


Figure 7. Cylindrical tube with longitudinal and transverse cuts. Tube length - 20 cm, transverse cut period - 0.5cm, tube radius – 0.9cm, wall thickness – 0.1cm, depth of transverse cuts – 0.25 of tube diameter

This system has been subjected to detailed research by modeling with a help of code CST MW SUITE. It was revealed, that the spectrum of mode is rather rarefied. The nearest mode will defend from a zero-mode far enough to not interfere with process of excitation. It is confirmed by the resonant curve of excitation of the zero-mode received at modeling. It is shown on a Fig. 8

High quality factor of system which can be considered as the open resonator makes size ~25. On Fig.8 the distribution of electric field amplitude in a plane x=const, passing through working gaps is resulted. The distribution is received for the cylindrical initiator with length of 20cm, radius 0.9cm and 40 working gaps at excitation on m=0 resonant frequency 2.35 GHz (λ= 12.77cm).

It is necessary to note, that within the limits of the resonant curve, shown on Fig.8, distribution remains same homogeneous, as on Fig. 6

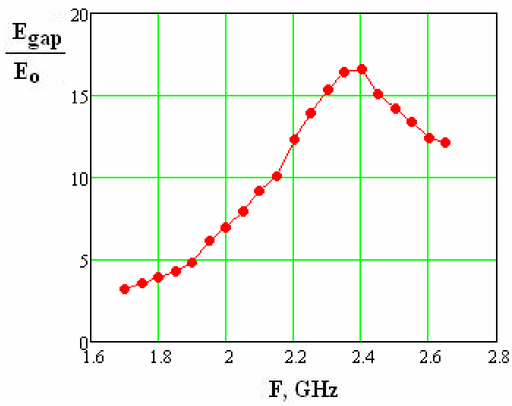


Figure 8 Resonant curve of zero-mode for system of Fig.7

In the received data the maximal field in gaps exceeds external field of MW radiation in 15-16 times. It is necessary to consider, that restrictions on cell size of a settlement grid do not allow receiving true value of the maximal intensity of a field on edges. True value of a field on edges which determines an opportunity of breakdown is many times more and, apparently, can come nearer to the values received in system of ring vibrators (more than 300 at a sufficient point of electrodes). The further settlement-theoretical and experimental operational development of the cylindrical initiator, certainly, will give the device for reliable excitation of homogeneous system of local discharges with the set period.

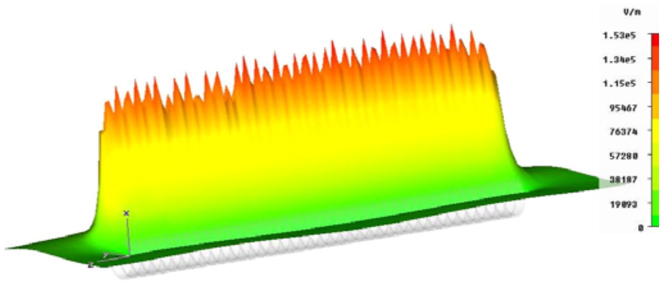


Figure 9. Distribution of electric field amplitude in plane, passing through axis of system and working gaps. Length of system - 20 cm, tube radius – 0.9 cm, Number of gaps – 40.

Basing on factor of increase of maximal field in gaps of the order 300, it is possible to accept, that for breakdown of air of atmospheric pressure by means of the cylindrical initiator the electric field with amplitude ~100V/cm (directed across an axis of the cylinder) is required. This value is realized in the lead experiments and should be specified experimentally for the initiator of offered type.

For excitation of investigated system by MW radiation with the specified level of amplitude of electric field E_o the power in beam of MW radiation is required

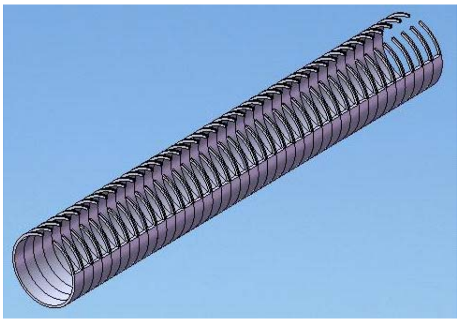
$$P_{MW} \approx \frac{c}{8\pi} \cdot |E_o|^2 \cdot S \,, \quad \text{erg/s,}$$

where c – light velocity, S - the area of cross-section of MW radiation beam in a plane of being excited system. Believing for an estimation

$$S = S_{\min} \approx (L + \lambda) \cdot \lambda \,, \ \text{cm}^2,$$

where L - length of system, λ- wavelength of MW radiation, and substituting mentioned above values, we shall receive minimally necessary power in a beam of 5.3 kW.

Maintenance of passage of beam of MW radiation within the limits of S_{min} is possible at enough perfect organization of antenna system and conditions of propagating in experimental volume. More real optimistic estimation is



(c)

(d)

Figure 10. Cylindrical initiator with various depth of transverse cuts: (c)- 0.25d, (d) – 0.9d

$$S \approx (L + \lambda)^2$$

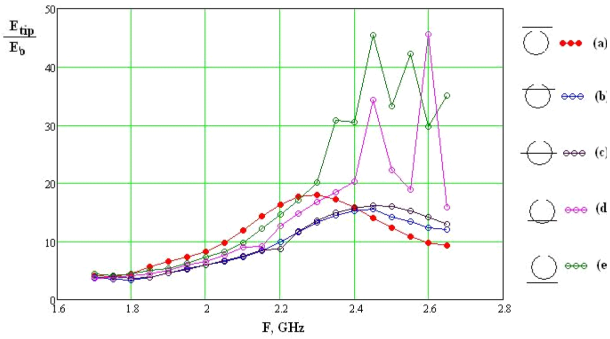


Figure 11. Dependence of maximum maximorum of electric field amplitude in the system on MW radiation frequency

Thus the necessary MW power makes 13.9kW. This value can be reduced due to use of the reflected radiation in a mode of a standing wave, as is realized in carrying out aerodynamic experiment where power of the generator equals to 7 kW in pulse.

Dispersive properties of the initiator representing the hollow metal cylinder with a longitudinal cut and periodic transverse cuts depend on depth of the last. For optimization of the system the row of models has been investigated numerically. Models of the cylindrical initiator at which depth of transverse cuts varies from zero up to full cuttings, investigated by numerical modeling, are presented on Fig.7 (model (a) with depth equaled 0), on Fig.7 (model (b) with depth equaled to 0.25 of diameter), on Fig.10 (models (c) and (d) with depth equaled to 0. 5 and 0.9 of diameter) and on Fig.3 (model (e) with depth excited diameter).

While depth of transverse cuts does not exceed half of tube diameter a kind of the characteristic varies a little, resonant frequency a little increases. Exclusively zero-mode corresponding to homogeneous distribution of amplitude on gaps is excited. At increase in depth of transverse cuts when or there is a narrow crosspiece between elements along system, or the cylinder is broken into the separate not closed rings (models (d) and (e)), on frequencies above 2.2 GHz occurs simultaneous excitation of the next modes, mainly to high number (up to 20-th). Distribution on gaps thus becomes unsuitable for use as contains plural failures up to zero (see Fig.11)

The most suitable model for the subsequent research is a cylinder with a longitudinal cut and periodic transverse cuts with depth 0.25 of the cylinder diameter.

Let's note, that value of the period poorly influences dispersive properties of the initiator.

IV. Summary

Thus, the further development of work as an integral part will contain:

- continuation of development of initiating system of new type, which contours are offered in the given paper,
- development of principles and methods of the organization of an electrodynamic environment of working area, both with reference to conditions of concrete experiment, and for typical conditions of forthcoming application of a developed method of influence on aerodynamic characteristics of structures.

It is necessary to notice, that the problem of the organization of distribution of MW radiation in conditions of concrete designs always will be an independent subject of researches and development.

V. Acknowledgments

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