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SYNTHESIS OF ARTIFICIAL GRAVITATIONAL FIELDS VIRTUAL METERS FOR THE POLYCONFLICTS RESOLUTION IN THE AERONAVIGATION ENVIRONMENT

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Abstract. *In article schemes have been offered and characteristics of virtual meters of artificial force fields for the conflicts resolution in the aeronavigation environment have been investigated.*

Keywords: barycentric system, gravitational fields, CNS/ATM environment, concept “Free Flight”, virtual meter.

Introduction

The currently used air traffic control system has reached limit of its capacity. Between overworked controllers and antiquated patchwork equipment, the ability to manage increasingly congested airways has become the subject of valid scrutiny. Compounding that concern, it is estimated that passenger traffic is growing by seven percent per year [1].

The overhaul process, a worldwide effort, has started. One of the cornerstones of the next generation of air traffic is a free flight concept [2−4].

Free flight refers to aircraft flying optimal routes, rather than using the airways. Navigation for free flight aircraft uses the satellite-based Global Navigation Satellite Service rather than radar. The benefits of free flight are many. Among the most frequently cited benefits are reduced flight times and improved fuel efficiency for aircraft. The greatest benefit may be that of increased airspace capacity. Ending the current restriction of traffic to airway space, particularly in areas of no radar coverage, will decimate traffic density, allowing the expected growth in air traffic to occur without an increase in congestion.

Despite the slashing of traffic density, aircraft conflict probabilities will never be zero, and therefore the need for conflict resolution services will persist after the introduction of free flight. Although conflict may arise less frequently, the additional freedom awarded to aircraft will make the conflicts that do occur more complex and controllers will no longer be able to rely on the structure of airways in determining resolutions. In addition, it is possible that a large number of aircraft will be affected by the outcome of the resolution leading to a large “ripple effect” or “domino effect”.

System stability is related to the system variables that give rise to the potential of a “domino effect”, where the resolution of a conflict between two aircraft propagates into causing a subsequent conflict with three or more aircraft before the conflict can be resolved.

Automated tools that aid in the resolution of conflicts have been developed, and one of the most prominent systems is the Traffic Alert and Collision Avoidance System (TCAS). However, possibilities TCAS are limited by the resolution of only pair conflicts [5].

In general, prior approaches to resolve air traffic conflicts in the context of free flight used expert systems and rule based systems. The disadvantages of these systems are their computational complexity, and the fact that rules used therein are not complete, in that, what to do in case that a situation not covered by the rules is encountered cannot be resolved.

Problem statement

In the work [6] the description of the aeronavigation environment objects by base of energy-potential model is considered. Material objects gravitational properties of the real world are a basis of this model. This makes it possible guarantee to solve polyconflicts problem in ANS at system level.

The model is based on a method known in the literature under various names:

- Potential Field Approach method;
- Artificial Potential Fields method;
- Virtual Force Field method;
- Vector Field Histogram method and others.

This method consist in use of the real world charged particles properties to generate a force field (electric or magnetic), which at their interaction causes attraction forces (for unequally charged particles) and repulsion (for equally charged particles). By analogy to the real world one sign virtual charges assign to mobile objects and obstacles in the aeronavigation environment, and opposite virtual sign charges assign to ultimate goals of mobile objects.

This method is most widely used in robotics. So in the works [7−10] use possibility of a potentials method in problems of a mobile robots way choice was considered.

Attempts of potential fields method use for resolution the conflict problems in aeronavigation environment have been undertaken in the works [11−13].

However, this method has some essential drawbacks not allowing its full use for the resolution of conflict problems in aeronavigation environment.

These drawbacks are:

– Presence of local minima in structure of potential fields that complicates gradient calculation;

– Essential decrease in speed of mobile object at the approach to an obstacle and in the process of its rounding (so-called braking or trample before an obstacle);

– Generating of trajectories which cannot be implemented aircraft.

Problem definition

The objective of this article is consideration of the method for resolving air traffic conflicts in the context of free flight.

Article purpose is the development of virtual measuring system of artificial force fields which eliminates the specified drawbacks of the potential fields method and emoves the restriction on use of this method for conflict problems resolving in aeronavigation environment.

Propose approach

To eliminate the above-mentioned drawbacks of the potential fields method it is proposed to use a virtual meter which is similar to a mobile mechanical system. This system is formed by one or two material points possessing mass. Material points are fixed on the ends of a rigid axle. The proposed system has two important properties:

1. Position of the mass centre of material points system does not depend on an order in which these points sequentially unite.

2. Position of the mass centre of material points system will not change if to replace some material points of their union.

In work use possibility of systems of virtual meters of classes “dipole” (fig. 1, *a*, *g*) and “pendulum” (fig. 1, *b, c, d, e, f*), consisting of n ≤ 2 mass has been considered.

Meters of class “dipole” are shown on fig. 1. Their barycenters 4 coincide with bracket points, and brackets meters of class “pendulum’ take places in a point 5 on the axle ends. The axle has a bracket point which arrangement coincides with the virtual meter mass centre (barycenter) [14].

The analysis of geometrical variety of virtual meters has shown, that schemes *a, b, c* shown in fig. 1 are unstable and further were not considered. Therefore schemes *d, e, f, g* meters have been investigated.

Analysis has carried out within the limits of the navigating space shown in fig. 2.

Researches of dynamics of virtual meters “dipole” and “pendulum” types have been carried out in work. This virtual meters are nonlinear kinematic models of integrated control in a conflict situation.

Virtual meters of “dipole type” *d, e, f* (fig. 1) and “pendulum type” are barycentric systems and as consistent with the nonlinear dynamic systems theory can be considered as analogues of “a controls cone” or “an accompanying cone” [15; 16].

Researches have been carried out for the purpose of revealing of trajectory behaviour features of mobile system with virtual meter of “dipole type” and “pendulum type” at passing and movement to the goal, revealing of virtual meter rational parameters and singular points of configuration space.

The model of dynamics of virtual measuring system generally is system of the equations:

$$\ddot{x}_i = \frac{1}{m_i}\sum_{i\neq j}^{N}\left(F_{xij} - W_{xij}\right);$$

$$\ddot{y}_i = \frac{1}{m_i}\sum_{i\neq j}^{N}\left(F_{yij} - W_{yij}\right),\ i\in N,\ \ j\in N,$$

where x_i, y_i – co-ordinates of *i*th body;

m_i – mass *i*th body;

F_{xij}, F_{yij} – attraction force acting between the bodies in the navigation space;

W_{xij}, W_{yij} – repulsion forces.

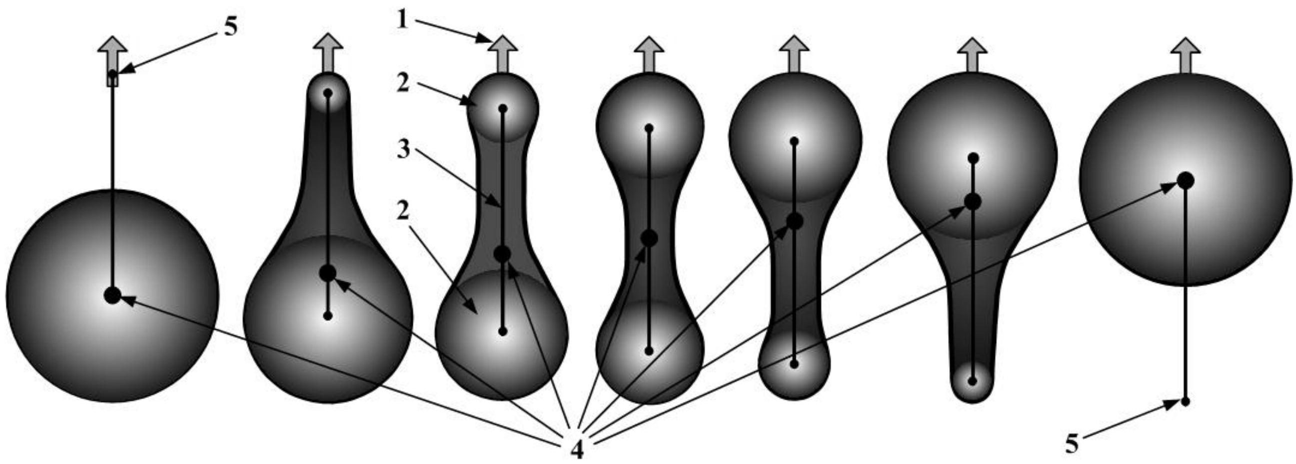


Fig. 1. Geometrical variety of virtual meters:
1 – movement direction of the virtual meter;
2 – the masses fixed of on the axle ends;
3 – the meter axle;
4 – virtual barycenters meters;
5 – bracket points of meters of class "pendulum"

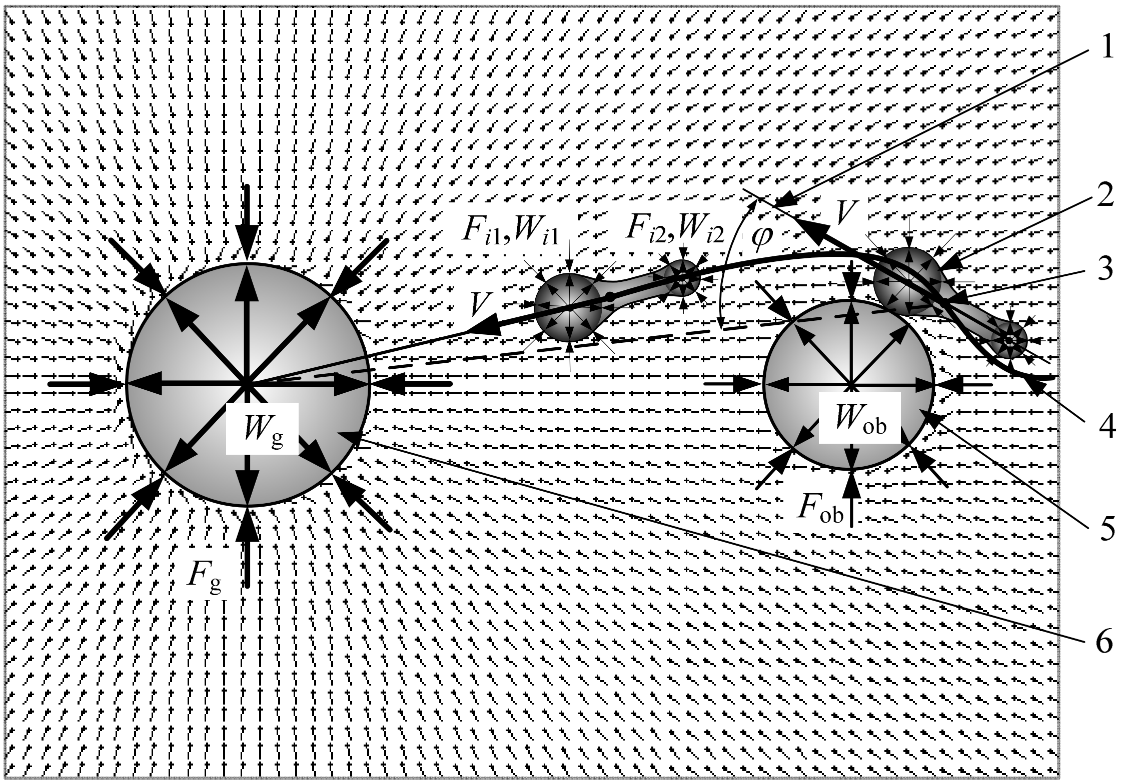


Fig. 2. The scheme of objects placing in navigating space:
1 – the virtual meter axle;
2 – the virtual meter of "dipole type";
3 – bracket points of meters (barycenter);
4 – movement trajectory of the bracket point of the meter;
5 – obstacle;
6 – goal

Projections of attraction and repulsion forces between *i*th and *j*th bodies on axes *X* and *Y* are calculated by the formulas:

$$F_{xij} = F_{ij}\frac{|x_i - x_j|}{R_{ij}},\ F_{yij} = F_{ij}\frac{|y_i - y_j|}{R_{ij}},$$

$$F_{ij} = \frac{Gm_i m_j}{R_{ij}^n}, \qquad (1)$$

$$W_{xij} = W_{ij}\frac{|x_i - x_j|}{R_{ij}},$$

$$W_{yij} = W_{ij}\frac{|y_i - y_j|}{R_{ij}},$$

$$W_{ij} = \frac{Gm_i m_j R_{cr}}{R_{ij}^m},$$

$$R_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2},$$

where G – gravitational constant, R – distance between bodies, R_{cr} – critical distance between the bodies, selected under conditions for security and conflict-free motion of dynamic objects in navigating space.

The summary gravitational forces acting on bodies form surfaces of levels (fig. 3).

Researches of three configurations of virtual meters have been carried out in the work. Parameters of experiments are resulted in table.

Parameters of the virtual meters

Expe-riment number	Virtual meters scheme	m_1, m_2	m_{ob}	m_g	λ (R_p)	R_{cr}
1	Fig. 4 (fig. 1, *d*)	m_1=m_2=0,5	m_1+ m_2	k(m_1+ m_2)	0,01 ... 0,99	0,5; 1; 2
2	Fig. 5 (fig. 1, *e*, *f*)	m_1=0,01 ... 0,99; m_2=1- m_1	m_1+ m_2	k(m_1+ m_2)	$R_{cm\ m1}$	0,5; 1; 2
3	Fig. 6 (fig. 1, *g*)	m_p=0,01 ... 0,99	1	km_{ob}	0,1 ... 1,4	0,2 ... 2,6

Foot-note: m_1, m_2 – bodies masses of the virtual meter; m_{ob} – obstacle mass; m_g – goal mass; m_p – pendulum mass; k – constant coefficient (k>>1); R_p – length of pendulum axle; λ – distance from mass m_1 to bracket of the meter of "dipole" type; $R_{cm\ m1}$ – distance from the dipole mass centre to mass m_1; R_{cr} – the critical radius at which is carried out equality of attraction and repulsion forces.

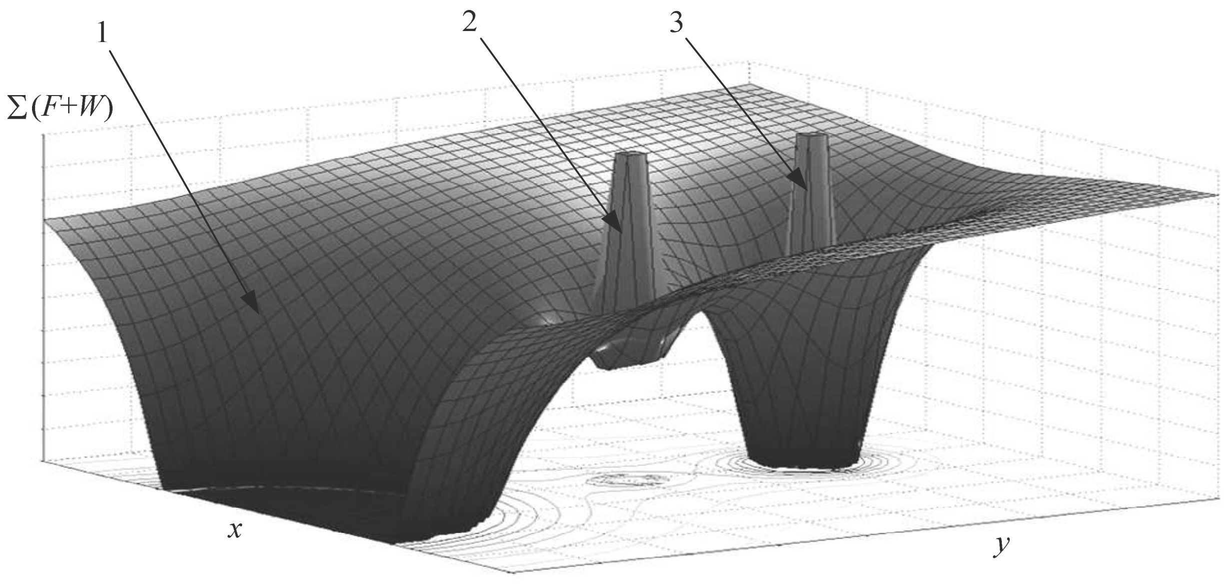


Fig. 3. The summary force field:
1 – goal area;
2 – mobile object area;
3 – obstacles area

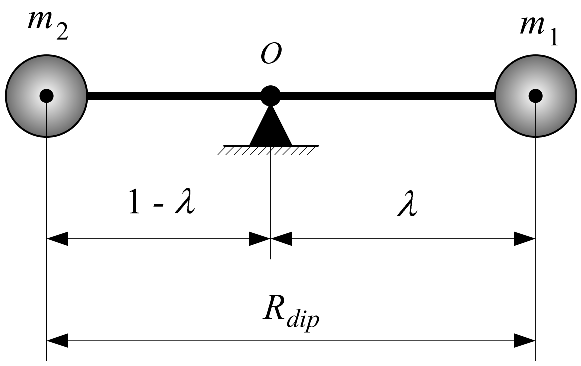


Fig. 4. The kinematic scheme of the virtual meter of “dipole” type at experiment 1

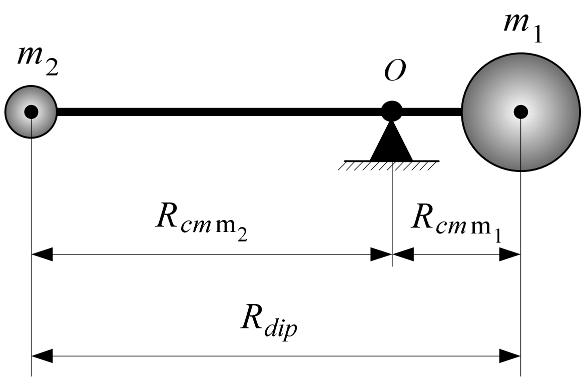


Fig. 5. The kinematic scheme of the virtual meter of “dipole” type at experiment 2

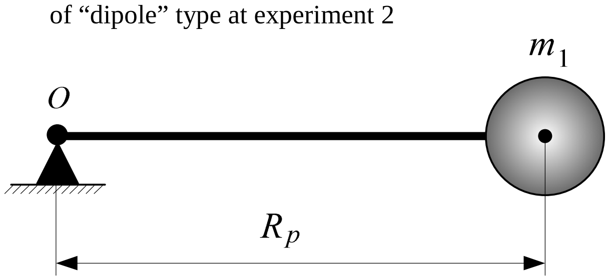


Fig. 6. The kinematic scheme of the virtual meter of “pendulum” type at experiment 3

Experiment 1. Object of research: the virtual meter of “dipole” type with identical masses on the ends of a rigid axle and a bracket point sliding along it. The kinematic scheme of system of a virtual meter is shown in fig. 4.

Characteristic results of modelling are shown in fig. 7.

Experiment 2. Object of research: the virtual meter of “dipole” type with varied masses on the ends of a rigid axle and the barycenter sliding along it. The kinematic scheme of investigated system is shown in fig. 5.

Characteristic results of modelling are shown in fig. 8.

Experiment 3. Object of research: the virtual meter of “pendulum” type with constant cargo mass on the one ends of rigid axle and the bracket in a point O on other end. The kinematic scheme of investigated system is shown in fig. 6.

Characteristic results of modelling are shown in fig. 9.

At research of virtual meter of “dipole” in experiments 1 and 2 topological features of dynamics of the this type of the meter have been revealed at obstacle. Such features is availability of two bifurcation zones on a site a avoidance obstacle trajectory by the meter. The first zone is characterised by “overturning” of an axle of the meter. Consequence is the deviation of a trajectory of movement aside, opposite to the purpose (fig. 7, *d*). As a result the movement trajectory deviates the goal in an opposite side (fig. 7, *d*). The second zone is characterised by “tightening” of the meter trajectory round the centre of mass of an obstacle in “spin” (fig. 7, *b*).

At large value R_{dip} and small λ_{m1} in the first zone strong fluctuation of a trajectory of the dipole bracket point caused by mass m_2 “beat” (fig. 7, *c*, *d*) can be observed. This effect can be eliminated at the expense of decrease of an integration step or by introduction of restriction on the increment of the dipole axle turn corner in regard to the bracket point or restrictions on a velocity vector deviation.

Research of the zone characterising tightenings of the mobile system trajectory in “spin” at obstacle avoidance, has been based on the analysis of the summary forces acting on masses m_1 and m_2 of the virtual meter of “dipole type”. It has been established that for elimination of effect of “spin” an attraction force of the goal acting on the dynamic object virtual meter should be more than the maximum value of the sum of attraction forces of other mobile and stationary objects which are in an affected zone. That is, the condition should be satisfied:

$$F_{ig} > \max \sum_{j=1}^{N} F_{ij}\ , \quad i \neq j\ , \qquad (2)$$

where F_{ig} – attractive force of goal i th dynamic object;

N – number of dynamic objects (without goals);

F_{ij} – attractive force i th dynamic object of j th dynamic object.

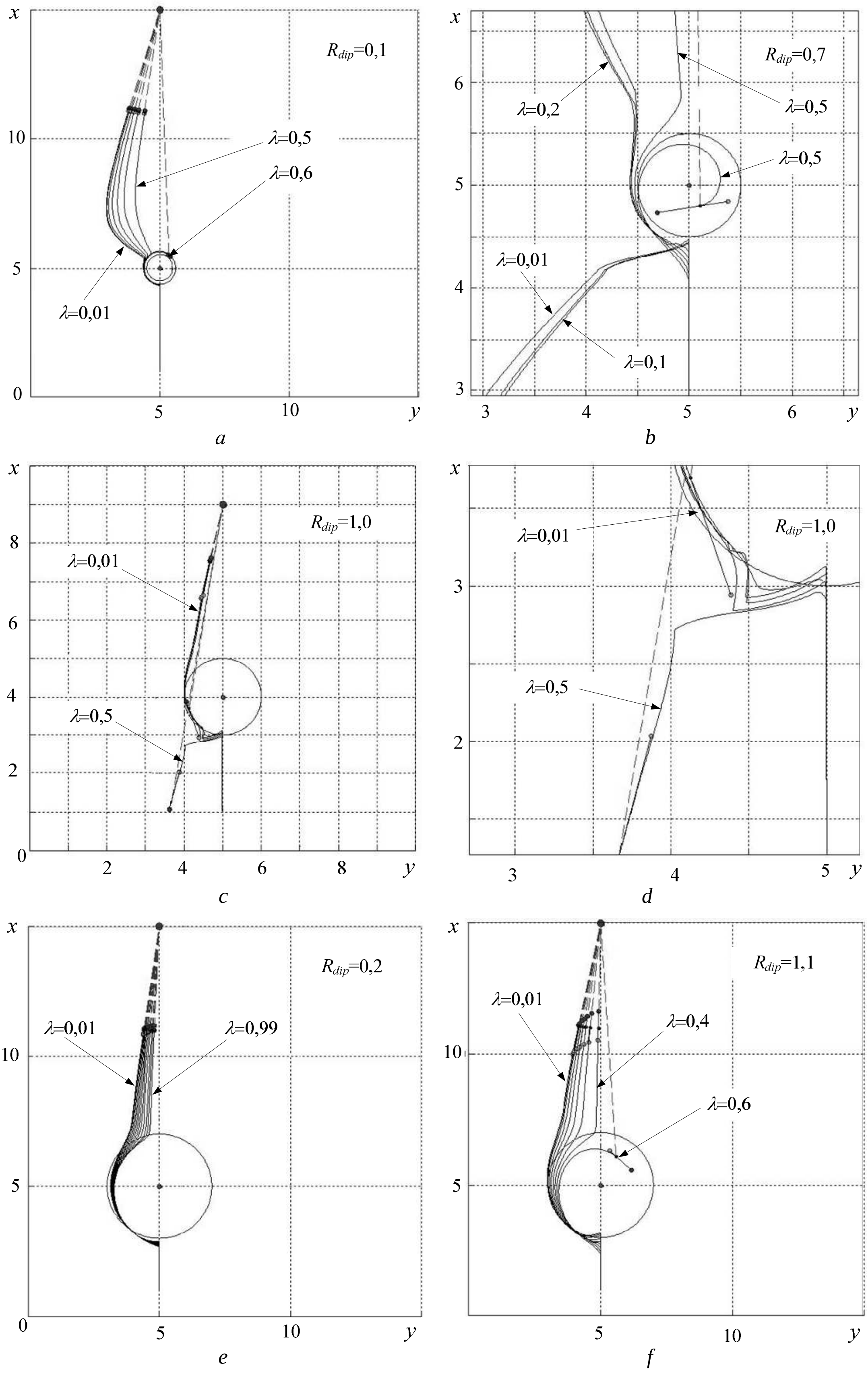


Fig. 7. Modelling results of dynamics of the virtual meter of “dipole” type at experiment 1 at various values of the set R_{cr}: *a*, *b* – R_{cr} =0,5; *c*, *d* – R_{cr} =1,0; *e*, *f* – R_{cr} =2,0

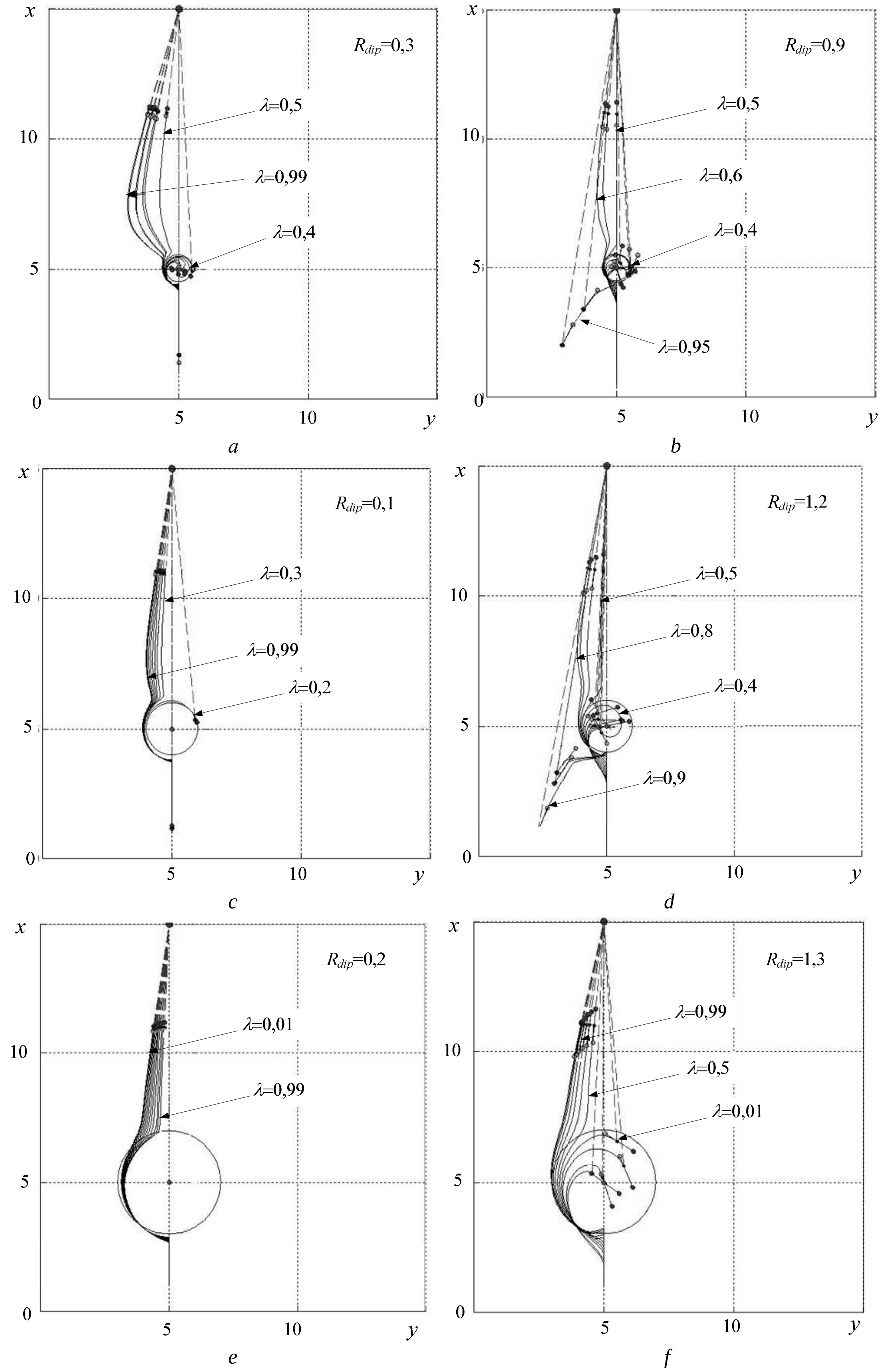
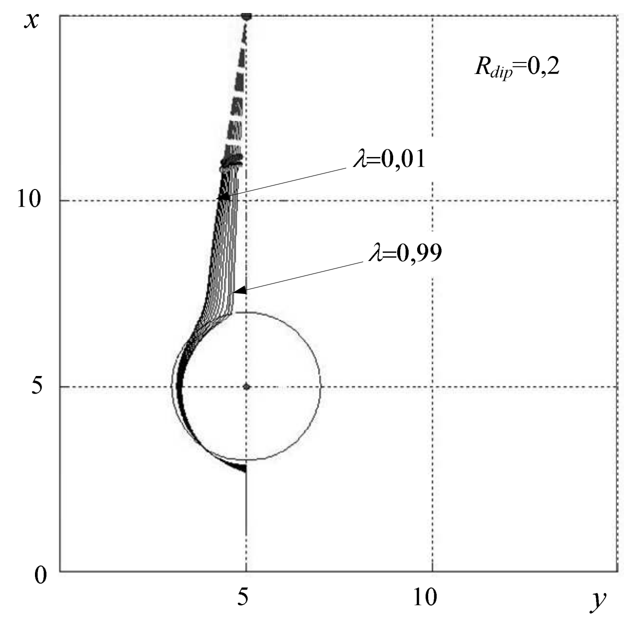


Fig. 8. Modelling results of dynamics of the virtual meter of “dipole” type at experiment 2 at various values of the set R_{cr}: *a*, *b* – R_{cr} = 0,5; *c*, *d* – R_{cr} = 1,0; *e*, *f* – R_{cr} = 2



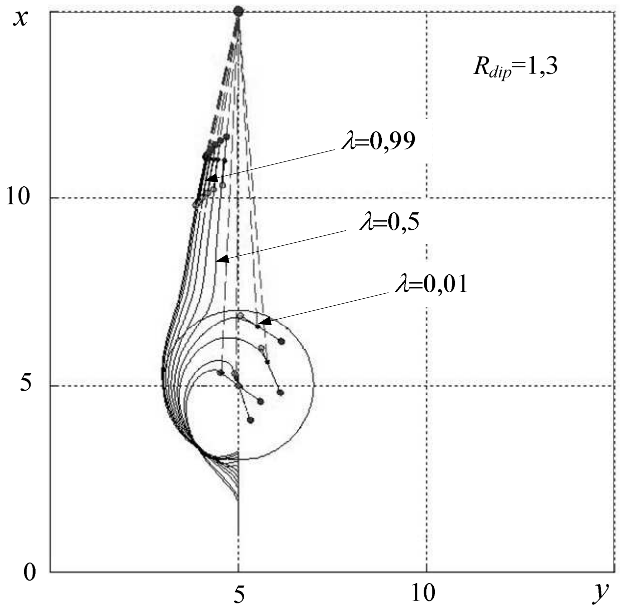


Fig. 9. Modelling results of dynamics of the virtual meter of “pendulum” type at experiment 3 at various values of the set R_{cr}:

a – R_{cr} = 0,6;

b – R_{cr} = 1,6

Concerning to conflicts resolution problems in aeronavigation environment the affected zone of gravitating objects is so-called Protected Airspace Zone [17].

Let's insert (1) in (2)

$$\frac{Gm_i m_{gi}}{R_{ig}^2} > \max\left(\frac{Gm_i m_1}{R_{i1}^2} + \frac{Gm_i m_2}{R_{i2}^2} + + \ldots + \frac{Gm_i m_N}{R_{iN}^2}\right), \quad (3)$$

where m_{gi} – goal mass of *i*th dynamic object.

Let's assume

$m_1, m_2, \ldots, m_N = 1$

and divide the left and right parts on Gm_i and multiply on R_{ig}^2:

$$m_{gi} > \max\left(\frac{R_{ig}^2}{R_{i1}^2} + \frac{R_{ig}^2}{R_{i2}^2} + \ldots + \frac{R_{ig}^2}{R_{iN}^2}\right). \quad (4)$$

Let's consider that $R_{iN} \approx R_{cr}$.

At $\max R_{ig} = 280$ км ($\approx$150 nm).

It fits to border of effective work ADS-B [18]:

$m_{gi} > N \cdot 10^5$.

If in (3) $m_1 \neq m_2 \neq \ldots \neq m_N$ then expression (4) is more difficult form:

$$m_{gi} > \max\left(\frac{m_i m_1 R_{ig}^2}{R_{i1}^2} + \frac{m_i m_2 R_{ig}^2}{R_{i2}^2} + + \ldots + \frac{m_i m_N R_{ig}^2}{R_{iN}^2}\right).$$

The estimation of use efficiency of virtual meters considered above has been carried by criterion of relative passed way S_r from a start point of mobile system with the virtual meter to intersection with a circle of the set radius whose centre is in a point of the purpose arrangement.

$$S_r = \frac{S_{mod}}{S_{str}}, \quad (5)$$

where S_{mod} – real (modeling) way which has been passed by the dipole bracket point;

S_{str} – the distance from the dipole start point to the point of the purpose arrangement.

The values shown in fig. 10 indicate a global minimum of this criterion for the corresponding parameter adjustments of virtual meters.

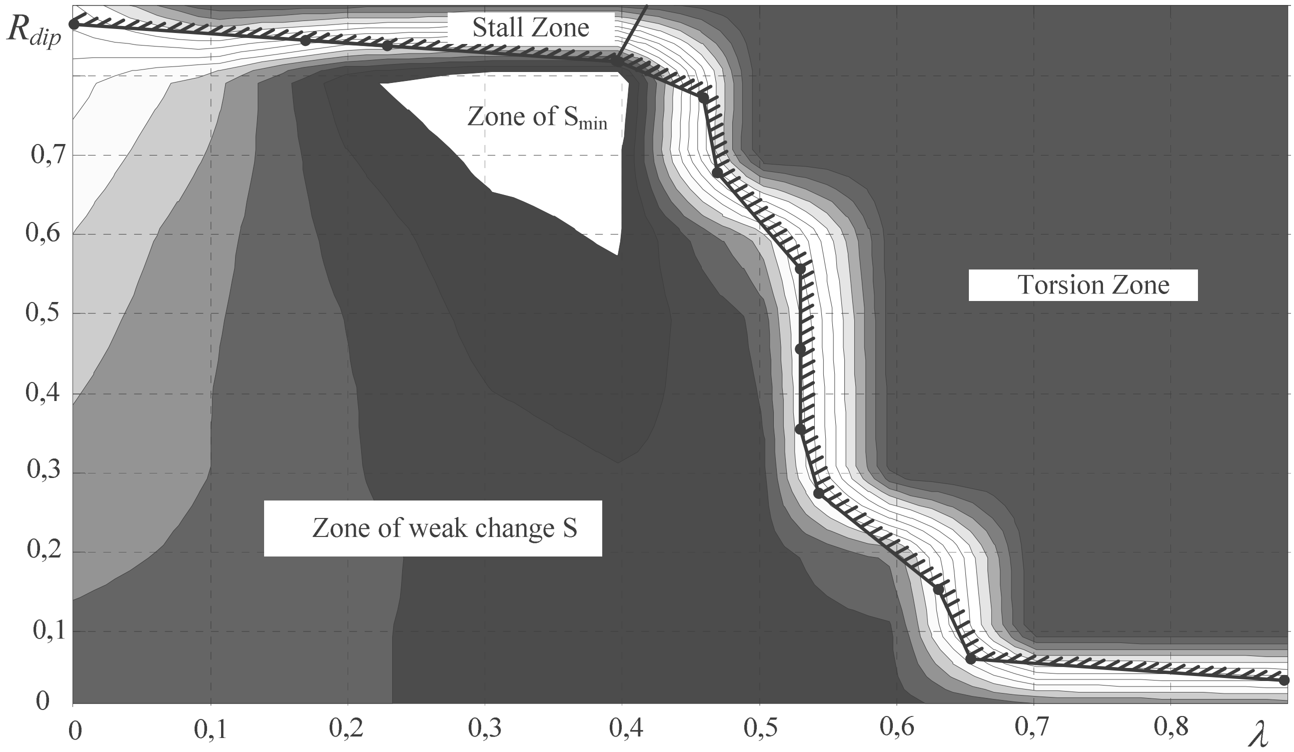


Fig. 10. Graphic representation of dependence $S_r=f(R_{dip},\lambda)$

This suggests to draw a conclusion that at the conflict problem solving corresponding adjustments of a virtual meter are capable to provide requirements of the minimum expenditure of energy on the conflict resolution.

Conclusions

Thus, the carried out analysis of dynamics of system parameters influence of virtual meters "dipole type" and "pendulum type" has shown:

1. The system "dipole" has a number of the essential drawbacks connected with effects of "overturning" and "spin" at obstacle avoidance. However these drawbacks are easily eliminated at a correct choice of meter parameters.
2. The choice of virtual meter parameters makes it possible to carry out the conflicts resolution in aeronavigation environment at maintenance of the minimum value of criterion of the relative passed way (5). Synthesised conflict-free trajectories have optimum time and energy expenditure at the conflicts resolution in aeronavigation environment.
3. The preference at a choice of the virtual meter for the conflicts resolution in aeronavigation environment is given to the meter of the class "pendulum" as it is free from drawbacks of the meter of the class "dipole".

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