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DOCKING OF SPACE VEHICLES IN "RUNNING MAGNETIC POTENTIAL WELL"

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The article concerns the problem of interaction of two superconducting arbitrarily disposed in space current circuits simulating the soft docking system of two objects in open space due to the magnetic interaction. Steadiness of such system was confirmed by means of Lagrange formalism and conditions of docking realization for two current coils were proved by the effect of running magnetic potential well.
KEYWORDS: magnetic docking, space vehicle, magnetic potential well, current coil, superconductivity, stability.

Docking of flying vehicles in open space is connected with difficulties of exact prompting and overlapping of objects. A significant quantity of on-board weight is spent. The application of magnetic docking does not require using a working body in ideal case. However a negative effect should be noted namely the decreasing control of the ship, which has magnetic dipole moment. This negative effect provides additional distortion of ship trajectory [1]. It is well known that the influence of small disturbance factors on the movement of a material system will be not identical for different type of movement. In this connection an establishment of attributes acquires large practical significance that enables to judge whether the mentioned movement is steady.

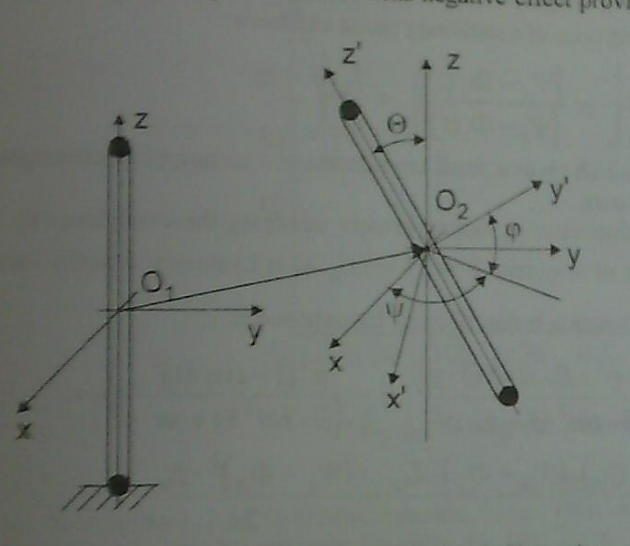

Fig. 1. Coordinate system of the superconductive docking units

We shall consider the scheme of magnetic docking of space vehicles, the elements of docking units of which contain the superconductive coil. Using engineering superconductors in space is perspective not only because of creation of strong magnetic fields and reduction of units dimensions of docking modules [2], but also because of maintenance of autofocusing of docking process which is considered below in details.

We combine a beginning of a cylindrical coordinate system with a center of weight of the first coil. As independent coordinates concern intersection of coordinates O_1 and Eu'er angles (Q, y, j) we shall choose coordinates z, r, θ, which are the coordinates of the second superconductive coil's center of weight (fig. 1). Thus a Q-angel and y-angle are the angles of nutation, j- is the angle of pure rotation. We shall denote an axial moment thorough **A** and equatorial moment of inertia of the second superconductive coil thorough **B**. The Lagrange function describes the interaction of two superconductive coils in a system of coordinates, which is connected with the first coil and has a form:

$$L_{lagr} = \frac{A\cdot(\dot{\varphi} + cos\,\Theta\cdot\dot{\psi})^2}{2} + \frac{B\cdot\left(\Theta^2 + sin^2\,\Theta\cdot\dot{\psi}^2\right)}{2} + \\ + \frac{m\cdot\left(\dot{z}^2 + \dot{\rho}^2 + \rho^2\cdot\dot{\alpha}^2\right)}{2} + \sum_i\sum_j \frac{L_{ij}}{2}\cdot I_i\cdot I_j + \sum_j I_j\cdot\Phi_j(t). \qquad (1)$$

Here **m**, (**z**, ρ, α) are the mass and the coordinates of a mobile superconductive coil center of inertia in a designated system of coordinates accordingly;

L_{ij} is the inductance ($i \neq j$) and the mutual inductance ($i \neq j$) of coils;

I_j is the current and Φ_i is the flow of external magnetic field through the i-th coil.

The Lagrange function contains cyclic coordinates. The first integrals of motion corresponding to these coordinates are:

$$\begin{cases} A\cdot(\dot\varphi+\cos\Theta\cdot[\dot\chi_1-\dot\chi_2])=a=const; \quad \chi_1=\dfrac{(\alpha+\psi)}{2}; \quad \chi_2=\dfrac{(\alpha-\psi)}{2}; \\ A\cdot\cos\Theta+\left(B\cdot\sin^2\Theta+m\cdot\rho^2\right)\cdot[\dot\chi_1+\dot\chi_2]=b=const; \\ L_{11}\cdot I_1+L_{12}\cdot I_2+\Phi_1(t)=\Psi_1=const; \\ L_{12}\cdot I_1+L_{22}\cdot I_2+\Phi_2(t)=\Psi_2=const. \end{cases} \tag{2}$$

We shall consider stationary motion $z=z_0(t)$, $\rho=0$, $\Theta=0$. Using the Routh function **R** we can get fid of cyclic coordinates, thus we have the lowered order of a system of differential equations, which describes the interactions of superconductive coils:

$$\mathbf{R}=\frac{dL_{lagr}}{d\dot\chi_1}\cdot\dot\chi_1+\frac{dL_{lagr}}{d\dot\varphi}\cdot\dot\varphi+\frac{dL_{lagr}}{dI_1}\cdot I_1+\frac{dL_{lagr}}{dI_2}\cdot I_2-L_{lagr}. \tag{3}$$

Then conditions of balance of two interacting superconductive coils, which are

$$z=z_0(t),\ \rho=0,\ \Theta=0, \tag{4}$$

will accept a form $\left.\dfrac{dR}{dz}\right|_0=0;\ \left.\dfrac{dR}{d\rho}\right|_0=0;\ \left.\dfrac{dR}{d\Theta}\right|_0=0.$ (5)

He system (5) gives us the conditions of Running magnetic potential well existence [3] in the system of coordinates z, ρ, Θ. The first equation defines the conditions of a stationary phase existence:

$$\left.\frac{[\Psi_1-\Phi_1(t)]}{[\Psi_2-\Phi_2(t)]}\right|_0=\left.\frac{L_{12}}{L_{22}}\right|_0 \quad \text{or} \quad \left.\frac{[\Psi_2-\Phi_2(t)]}{[\Psi_1-\Phi_1(t)]}\right|_0=\left.\frac{L_{12}}{L_{22}}\right|_0. \tag{6}$$

The choice of equalities (6) is defined by contour, which gives a small amendment in a picture of electromagnetic fields distribution of two interacting superconductive contours.

We shall consider stability of process of superconductive coils rapprochement satisfying the conditions (5). We shall take a difference between two Hamilton functions of a system $V=H-H|_0$ as a Lyapunov function, where $H|_0$ means undisturbed condition [4], and the Hamilton function is described by the expression:

$$\mathbf{H}=\frac{B\cdot\Theta^2}{2}+\frac{m\cdot(z^2+\rho^2)}{2}+2\cdot\frac{m\cdot\rho^2\cdot B\cdot\sin^2\Theta\cdot\chi_2^2}{B\cdot\sin^2\Theta+m\cdot\rho^2}+\frac{a^2(1-\cos\Theta)^2}{2\cdot(B\cdot\sin^2\Theta+m\cdot\rho^2)}+$$
$$+\frac{(\Psi_1-\Phi_1)^2\cdot L_{22}}{2}++\frac{2\cdot(\Psi_1-\Phi_1)\cdot(\Psi_2-\Phi_2)\cdot L_{12}}{2}+\frac{(\Psi_2-\Phi_2)^2\cdot L_{11}}{2}. \tag{7}$$

The process of rapprochement will be steady if the function **V** in a vicinity of a state of balance is nonnegative relatively to z, ρ, Θ and if V satisfies the condition $\dfrac{dV}{dt}\le 0$.

We shall operate with the process of docking by changing the magnetic flow Φ in the first coil. It follows from the inequality $\dfrac{dV}{dt}=-I_1\dfrac{d\Phi_1}{dt}\le 0$, condition (6), and after simple transformations $\dfrac{d\Phi_1}{dt}>0$, where $\left|\dfrac{\Phi_1}{\tau}\right|>>\left|\dfrac{d\Phi_1}{dt}\right|$ and τ is a characteristic time of the process.

It is possible to simulate the toroidal superconductive coils with a sufficient degree of accuracy using infinitely thin ideally conducting spire with radius much exceeding a small one.

Taking into consideration the conditions (6), it may be easily shown that the Lyapunov function recorded with accuracy up to the members of second order as to small perturbations is nonnegative. The last circumstance requires the consideration of Lyapunov function with accuracy to the members of the fourth order as to small perturbation inclusively:

$$\mathbf{V}=\frac{a^2\cdot(1-\cos\Theta)^2}{2\cdot(B\cdot\sin^2\Theta+m\cdot\rho^2)}+\frac{1}{2}\cdot\left.\frac{\partial^2W}{\partial z^2}\right|_0\cdot(z-z_0)^2+$$

$$+\frac{1}{8}\cdot\frac{\partial^2 W}{\partial L_{12}^2}\bigg|_0\cdot\left(\frac{\partial L_{12}}{\partial z}\bigg|_0\cdot(z-z_0)^2+\frac{\partial L_{12}}{\partial \rho}\bigg|_0\cdot\rho^2+\frac{\partial L_{12}}{\partial \Theta}\bigg|_0\cdot\Theta^2\right)^2+\left(0^5\right), \qquad (8)$$

here $W=\frac{(\Psi_1-\Phi_1)^2\cdot L_{22}-2\cdot(\Psi_1-\Phi_1)\cdot(\Psi_2-\Phi_2)\cdot L_{12}+(\Psi_2-\Phi_2)^2\cdot L_{11}}{2}$.

The Lyapunov function is quite positive in vicinity of state Magnetic potential well as to small perturbation of variables $z=z_0(t)$, $\rho=0$, $\Theta=0$ during the whole process of coils rapprochement. Having supplied slow change of a magnetic flow of an external magnetic field $\Phi_1(t)$, $\left|\frac{\Phi_1}{\tau}\right|>>\left|\frac{d\Phi_1}{dt}\right|$ we can see that the docking process will be steady all along the docking if the following conditions are fulfilled

$$\frac{\left[\Psi_1-\Phi_1(t)\right]}{\left[\Psi_2-\Phi_2(t)\right]}\bigg|_0=\frac{L_{12}}{L_{22}}\bigg|_0,\ \frac{d\Phi_1}{dt}>0. \qquad (9)$$

It should be noted, that the maintenance of stability of Θ is possible because of a gyroscopic effect, and maintenance of stability of z and ρ is possible because of Running magnetic potential well effect.

The diagram of a magnetic potential energy gradient depending on the z-coordinate (see fig. 2) illustrates particular behavior of a magnetic interaction force, which provides the system steadiness.

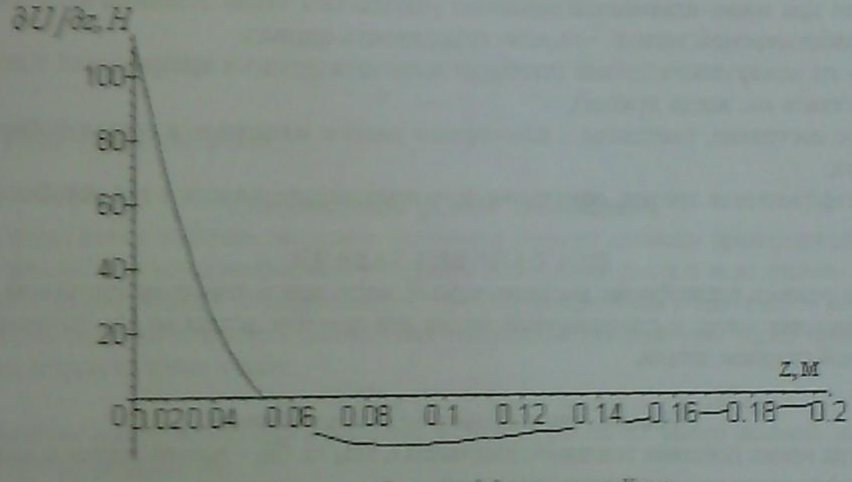

Fig. 2. The magnetic potential energy gradient

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СТЫКОВКА КОСМИЧЕСКИХ ЛЕТАТЕЛЬНЫХ АППАРАТОВ В «БЕГУЩЕЙ МАГНИТНОЙ ПОТЕНЦИАЛЬНОЙ ЯМЕ»

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В статье рассмотрена проблема взаимодействия двух сверхпроводящих произвольно расположенных в пространстве токовых контура, моделирующую систему мягкой стыковки двух объектов в открытом космосе. Устойчивость такой системы подтверждена решением задачи их взаимодействия с использованием Лагранжевого формализма и условиях реализации стыковки для двух токовых колец за счет проявления эффекта «бегущей магнитной потенциальной ямы».

КЛЮЧЕВЫЕ СЛОВА: магнитная стыковка, космический летательный аппарат, магнитная потенциальная яма, токовый виток, сверхпроводимость, устойчивость.