

THREE-POINT GRIP IN WEIGHTLESSNESS

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ABSTRACT. By ensuring secure logistics in the Solar System, it is possible to launch a space industry, which will initially be carried out by extracting minerals and fuels from space bodies. First, these will be small space bodies, such as meteorites and comets, and later we will proceed to mastering space bodies like planets. This in turn requires a direct connection between astronautics and robotics, requiring a drastic change in the design of spacecraft. It is of great importance to study the physical phenomena associated with the grip of two or more bodies in weightlessness. The present material will try to shed some light in this area.

Key words: support, grip, space body, space industry.

ТРИТОЧКОВ ЗАХВАТ В УСЛОВИЯТА НА БЕЗТЕГЛОВОСТ

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РЕЗЮМЕ. При осигуряване на сигурна логистика в Слънчевата система е възможно стартирането на космическа промишленост, която ще се осъществи първоначално с добиването на полезни изкопаеми и горива от космическите тела. Това първоначално ще са малките космически тела като метеорити и астероиди, като в последствие ще се пристъпи и към овладяването на космически тела от рода на планетите. Това от своя страна налага пряка връзка между космонавтиката и роботиката, изисквайки драстично изменение на конструкцията на космическите кораби. От голямо значение е да се изучат физичните явления свързани със захвата на две и повече тела в условията на безтегловност. Настоящия материал ще се опита да хвърли малко светлина в тази област.

Ключови думи: опора, захват, космическо тяло, космическа индустрия.

Introduction

All meteorites considered in this material are assumed to have no self-gravity, and there are no forces acting between the spacecraft and the space body. The issue is discussed in more detail in “Opportunities for creating industry outside Earth” (Sinilkov, 2024). Regarding the size of the asteroids considered in the material, these are space bodies that are the maximum approximate size of the spacecraft (i.e. the two engaging bodies are comparable) or slightly larger than the spacecraft. Details can be found in “Nyakoi vazmozhnosti na transportnite sredstva pri dobiva na polezni izkopaemi ot kosmicheski tela” (Sinilkov, 2023).

Usually, when two bodies come into contact, many physical phenomena occur. One of them is the impact. It is known from the theory of impact that during an impact, the so-called impact force is exerted between the striking bodies for a very short time. To a large extent, this impact force is uncontrollable and leads to unpredictable destruction of both bodies, which must be avoided.

In this material, the situation of interest is when two bodies approach each other in outer space. An interesting hypothesis is presented in “Neobhodimostta ot vrazka na kosmonavtikata i robotikata pri dobiva na polezni izkopaemi ot kosmicheski tela” (Sinilkov, 2024), wherein one body (the spacecraft) captures the other body (the asteroid), that is, they merge into one body with minimal impact force between them. The method of synthesis of working bodies is described in “Analitichen sintez na mehanizmi za krainitsi na kracheshti mobilni roboti” (Sinilkov, 2011).

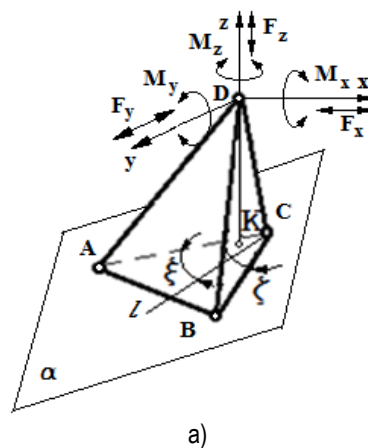
Method

Three-point support

Before considering the grip, the three-point support, which is a geometric-mechanical element of kinematic systems, will be briefly considered. The three-point support is practically the most stable of all supports known in mechanics and meets the minimum requirements of the geometric laws for determining a plane in space.

By definition from geometry, *every three points in space, not lying on a straight line, determine a plane in space.*

In mechanics, in the general case, the three-point support is considered as a triangular pyramid with height KD , where point D is the top of the pyramid above the plane determined by the three support points A, B , and C , in space (Fig.1.a).



a)

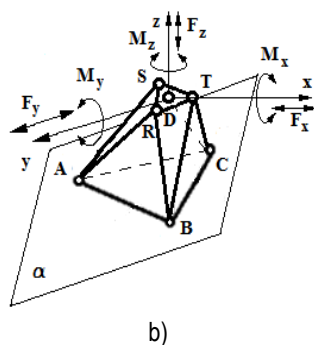


Fig. 1. Geometric representation of a three-point support (grip) on the plane; a) Basic pyramidal structure; b) The “Steward Platform” mechanism applied to the basic three-point support (grip)

A characteristic feature of the task is that the load on the system is concentrated at point D , that is, the top of the pyramid. This is a six-dimensional dynamic load, more precisely, these are three linear components along the three axes of the inertial coordinate system $xDyz$ in space and mutually perpendicular components of the moments along these axes.

$$\begin{aligned}\vec{F}^e &= \vec{F}_x + \vec{F}_y + \vec{F}_z \\ \vec{M}^e &= \vec{M}_x + \vec{M}_y + \vec{M}_z\end{aligned}\quad (1)$$

where:

$\vec{F}^e$ – the principal vector of all external forces for the system;

$\vec{M}^e$ – the principal moment of all external moments for the system.

It is important to note that the support reactions of this system depend not only on the magnitude of the principal vector of all external forces $\vec{F}^e$ and the principal moment of all external moments $\vec{M}^e$, but also on the length of the height of the pyramid DK .

Fig. 1.b) shows the “Steward platform” mechanism. At first glance, this construction is perfect for implementing a support or grip. However, this is not the case, since it can only be considered as a basic kinematic system for a three-point support and a three-point grip. Going deeper into the kinematic analysis of supports and grip, especially in weightless conditions, and especially taking into account the security of contact, it will be noticed that the three-point grip has developed into four-point, five-point, etc. In this development, it is clearly distinguished that the “Steward Platform” is only one basic kinematic structure that provides the basis for the construction of supports and grips.

For use in astronautics, the advantages of this basic mechanism are numerous. On this basis, many spatially closed kinematic systems are synthesised to cover the requirements of certain kinematic systems for support grips.

When considering a three-point support, the following are not mandatory:

1. These are monolithic bodies, as shown in Fig. 1. The important thing here is to determine the three support points A , B , and C defining the plane in space, as well as to determine the position of other characteristic points in space;

2. The support triangle ABC does not have to represent a

single unchanging geometric triangle. Of great mechanical importance in the distribution of the forces of the system is that the triangle ABC has the ability to change the sizes of its sides.

As a result of what was described above for the three-point support, it can be said that to find the support reactions of the system at points $(A, B$ and $C)$, a classical problem for finding support reactions is obtained, in which the most important thing is to ensure that the components that press the support triangle against the plane a do not become zero or take on a negative value.

Three-point grip

In the presence of support reactions that repel the support triangle from the plane a , the physical phenomenon of support cannot be realised. In the physical phenomenon of grip, the support reactions can acquire different values, without limitation, positive, zero or negative.

It should be immediately clarified that grip, as a phenomenon, has four phases of action:

1. Contact phase - this is the first moment of contact between the two bodies. This is the moment when the impact phenomenon is realised;

2. Grip phase - this is the phase in which a monolithic connection between the two bodies is realised. Here, forces appear between the two bodies, which are considered by mechanics as clamping forces;

3. A phase in which the physical phenomenon of grip ceases to exist and all its clamping forces are zeroed;

4. Repulsion phase or other impact between the two bodies. In this phase, forces acting after phase 3 are observed, which are *motor* for one body and *external* for the other body.

It should be clarified that there is a significant difference between the structural design of the three-point support and the three-point grip, even with the same external load. This mainly follows from the functions that the kinematic system must respond to in both types of execution.

Theoretical statements from the Theory of Impact

In the first phase of the grip, the physical phenomenon of impact occurs between the two bodies. Entering the theory of impact, the physical phenomenon of impact is characterised by an impact in a very small time interval. In this time interval, the so-called impact force acts, which takes on very high values.

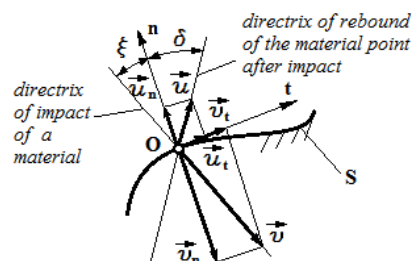


Fig. 2. Schematic diagram of the impact of a material point on a stationary surface

If we hit a material point with mass m on a stationary surface $S(x, y, z, t) = 0$, at an angle ξ to the normal n (Fig. 2) of the surface S , with a speed v , then the reaction to the impact will depend on the physicomaterial properties of the matter of the material point and the surface S , at the moment of impact. In this material we will limit ourselves only to the shape

of the bodies, assuming that the physicomaterial characteristics are uniformly distributed over the surface and volume of the bodies.

The normal to the surface at the point of impact is given by expression (2):

$$n = \text{grad } S(x, y, z, t) = 0 \quad (2)$$

At the moment of contact of the material particle with the surface S and upon leaving the point of contact, regarding the velocity (Fig. 2), the following equality holds:

$$\text{grad } S \cdot v + \frac{dS}{dt} \geq 0 \quad (3)$$

At the initial moment of impact t_0 , the basic equation of impact theory, projected onto the normal, takes the form:

$$\begin{aligned} mu_n - mv_n &= I_n^m \\ mu_t - mv_t &= I_t^m \end{aligned} \quad (4)$$

This system of equations is indeterminate because the equations are two and the unknowns are four, i.e. I_n^m , I_t^m , u_t and u_n . Newton added two additional empirical relationships, based on a large number of experiments and observations.

The ratio of the absolute values of the normal projections of the relative velocities from the second and first phases of the impact is a constant value and depends only on the physicomaterial properties of the matter.

$$\frac{u_n}{v_n} = \rho \quad (5)$$

This coefficient is called the coefficient of recovery. It varies between 0 and 1, i.e. $0 < \rho < 1$. At $\rho = 0$ there is a completely plastic impact, that is, there is no second phase of the impact (there is no movement after the first phase, in other words, all the energy of the impact is spent on plastic deformation). At $\rho = 1$ there is a completely elastic impact, that is, there is a complete recovery of the movement after the impact, albeit in a different direction.

The ratio of the absolute values of the tangential projections of the relative velocities from the second and first phases of the impact is a constant value and depends only on the physical and mechanical properties of the matter.

$$\frac{u_t}{v_t} = 1 - \lambda \quad (6)$$

Where: λ is called *the coefficient of instantaneous friction*.

The two empirical relationships introduced by Newton make it possible to solve the equations and find the velocities and impulses during the impact.

As is evident from the above considerations, the impact theory is not an exact theory built on the basis of precise physical quantities and their specific change depending on the change in the surrounding conditions. This is an approximate theory, but it is still based on numerous experiments and the results have been confirmed by practice with satisfactory accuracy.

The relationship between the angle of attack ξ and the angle of reflection after the impact δ is as follows:

$$\tan \xi = \frac{v_t}{v_n}, \tan \delta = \frac{u_t}{u_n} \quad (7)$$

or

$$\frac{\tan \delta}{\tan \xi} = \frac{1 - \lambda}{\rho}$$

The magnitude of the shock impulse is found by the formula:

$$I^m = \sqrt{(1 + \rho)^2 \cos^2 \xi + \lambda^2 \sin^2 \delta} \quad (8)$$

Kinetic energy upon impact of a material point. Loss of kinetic energy. The momentum of the system has the form:

$$mu - mv = I^m \quad (9)$$

After multiplying both sides by u and v respectively, we get:

$$\begin{aligned} mu^2 - mu \cdot v &= I^m \cdot u \\ mu \cdot v - mv^2 &= I^m \cdot v \end{aligned}$$

After conversion, we get:

$$\frac{mu^2}{2} - \frac{mv^2}{2} = \frac{1}{2} I^m \cdot (v + u) \quad (10)$$

An equality is obtained, which shows that the change in kinetic energy when a material point hits a surface is equal to the product of the impulse of the impact force and half the sum of the attack velocity and the reflected velocity.

The kinetic energy lost as a result of this phenomenon is:

$$\Delta T = -\frac{1}{2} m(v - u)^2 \quad (11)$$

Carnot's theorem expresses the loss of kinetic energy using the coefficient of restitution:

$$\Delta T = -\frac{1}{2} m \frac{1-\rho}{1+\rho} (v - u)^2 \quad (12)$$

At $\rho = 1$, there is a completely elastic impact and $\Delta T = 0$, that is, there is no loss of kinetic energy. At $\rho = 0$ there is practically no second phase of the impact and all the kinetic energy is lost.

When the kinetic energy changes in a mechanical system, Carnot's theorem takes the form:

$$\Delta T = -\frac{1-\rho}{1+\rho} \sum_{i=1}^n \frac{1}{2} m_i (v_i - u_i)^2 \quad (13)$$

where i is the number of participating material objects in the mechanical system.

Depending on the position of the normal to the surface at the point of impact, whether it passes through the mass centers of the bodies or not, we distinguish between a straight and an oblique impact.

Two bodies make a straight impact if the line connecting their centers of gravity is a common normal at their point of contact and the velocities of their centers of gravity before the impact are directed along this normal. Since a straight impact is an extremely rare phenomenon in grip in weightlessness, its

consideration is deliberately omitted.

Oblique impact of two bodies. The impact of two bodies is called oblique if the absolute velocities of their centers of gravity are not directed along the line connecting them.

$$m_1 \cdot u_1 + m_2 \cdot u_2 = m_1 \cdot v_1 + m_2 \cdot v_2 \quad (14)$$

The mathematical approach is analogous to the impact of a material point on a stationary surface. Projecting this equality onto the normal and tangent at the point of contact, we get:

$$\begin{cases} m_1 \cdot u_{1n} + m_2 \cdot u_{2n} = m_1 \cdot v_{1n} + m_2 \cdot v_{2n} \\ m_1 \cdot u_{1\tau} + m_2 \cdot u_{2\tau} = m_1 \cdot v_{1\tau} + m_2 \cdot v_{2\tau} \end{cases} \quad (15)$$

There are four unknowns in this system of two equations, and to fully determine it, we add the two empirical relationships from Newton's theorem for the coefficients of restitution and instantaneous friction.

$$\rho = -\frac{u_{1n} - u_{2n}}{v_{1n} - v_{2n}} \quad \lambda = -\frac{u_{1\tau} - u_{2\tau}}{v_{1\tau} - v_{2\tau}} \quad (16)$$

Minimisation of impact force. According to the conditions of the task, impact forces can be destructive for some types of meteorites, and for missiles (for the level of existing technology at the moment), these forces are disastrous. The solution is to minimise the impact forces at the moment of capture, damp them in time or zero them, if possible.

On this basis, many types of capture designs are possible, which can absorb impact forces and moments in the specified directions. The following options are possible:

1. There is a complete loss of kinetic energy, that is:

$$\Delta T = \max, \quad \rho = 0 \quad (17)$$

In this case, the coefficient of restitution is zeroed and there is a completely plastic impact, that is, all the kinetic energy is spent on changing the shape of the two captured bodies. Since the properties of the matter of the space body are unknown, the kinematic system of the spacecraft's capture must ensure the zeroing of the coefficient of restitution;

2. When the magnitude of the impact impulse is zeroed:

$$I^m = \sqrt{(1 + \rho)^2 \cos^2 \xi + \lambda^2 \sin^2 \delta} = 0 \quad (18)$$

Since momentum is a quantity obtained as a product of mass and velocity, in order to reset the momentum, the velocity must be reset (the option to reset the mass is not relevant, because this means that there is no body). Structurally, this is achieved by moving the three points A, B, and C of the support triangle so that it resets the coefficients of restoration and instantaneous friction.

The synthesis of the kinematic structure that will realise the grip and connect the two bodies and manipulate the position between them starts from the support triangle ABC and provides a conceptual opportunity for:

- Kinematic synthesis of a kinematic system in order to regulate the support reactions at the three points (vertices) A, B, and C of the support triangle of the grip;
- Constructive realisation of the damping capacity of the kinematic system;
- The possibility of maneuvering (manipulation) and changing the position between the two gripped bodies.

Phase 3 and phase 4 are realised by the action of the kinematic system of the spacecraft and to a greater extent affect its movement.

Some types of schematic solutions of kinematic chains of three-point support and three-point grip for the realisation of locomotion.

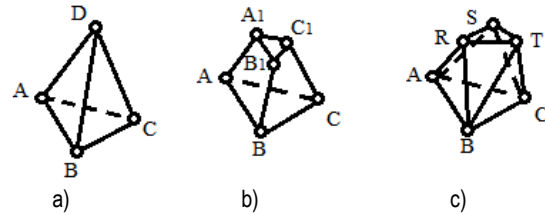


Fig.3 Development of the pyramidal structure of a three-point grip

The three types of kinematic structures of a three-point hitch shown in Fig. 3 show how the kinematic structure of a three-point hitch can be structurally modified, starting from the support triangle ABC. This is only an example demonstration of a structural modification.

In position a) in Fig. 3., there is a classic pyramid, where all the links of the pyramid can be extended or contracted.

In position b) in Fig. 3., the pyramidal structure has the shape of a truncated pyramid, in which the unit A1B1C1 is solid. In other words, point D has become a triple unit.

In the third position c) in Fig. 3., the pyramidal structure has become a "Stuart's platform", the mechanism well-known from the theory which has many advantages from the point of view of mechanics.

The synthesis of the kinematic structure, starting from the support triangle, provides a conceptual opportunity for:

- Kinematic synthesis of a kinematic system in order to regulate the support reactions at the three points (vertices) of the support triangle of the grip;
- Constructive realisation of the damping ability of the kinematic system;
- The possibility of maneuvering (manipulation) and changing the position between the two bodies.

Phases 3 and phase 4 are realised by the action of the kinematic system of the spacecraft and to a greater extent affect its movement.

Conclusion

Space industry requires continuous interception of meteorites, transportation to a certain place, and unloading. Therefore:

I. The spacecraft that implements this must have reliable gripping mechanisms;

II. These mechanisms must provide a secure grip so that the rocket and the space body at a given moment constitute a solid and indestructible monolithic whole;

III. In practice, kinematic schemes are constructed that are hybrid, depending on the distribution of support reactions, some of the points in the support triangle or polygon are support, and the rest are gripped.

Here on Earth, in the biomechanics of animals, insects, birds, etc., which land on flowers, trees, or other animals, or climb on them, have limbs that minimise impact forces. The goal is not to transmit kinetic energy to the surrounding structures in their habitat, as this can trigger someone's movement receptors. This incredible similarity between the approach in nature when building supports and grips in technology shows the accuracy of the method for constructive synthesis of supports and grips.

This requires that the structures of spacecraft undergo significant changes, acquiring a new appearance that is adapted for production activities in the conditions of weightlessness.

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