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MOVEMENT OF TANDEM MAGNETIC NANOPARTICLES IN AN ALTERNATING MAGNETIC FIELD

N. A. Beissen*, G. B. Serikakhmetova, M. E. Abishev

Al-Farabi Kazakh National University, Almaty, Kazakhstan

E-mail for contacts: nurzada.beissen@kaznu.edu.kz

This research article considers the tandem magnetic nanoparticles, which consists magnetic nanoparticle, connected with functional nanoparticle by carbon nanotube, exploring the transformative impact of temporal changes in magnetic fields on their behavior. By manipulating magnetic induction, using sifted center of mass such nanoparticles and necessary angle between its axis and magnetic dipole moment, we can exercise precise control over the movement of such nanoparticles. This holds immense promise for various applications, particularly in the field of medicine.
Nanotechnology has a wide range of applications in the medical field, particularly as nanomedicine. Some nanoparticles are promising for new diagnostic tools, imaging techniques, targeted therapies, pharmaceuticals, biomedical implants, and tissue engineering. Nanotechnology allows for the safer administration of high-toxicity treatments, such as chemotherapy drugs for cancer. Additionally, wearable devices can monitor vital signs, detect cancer cells, and identify infections in real time. These advancements are expected to give doctors significantly better access to critical information about the causes of changes in health, directly from the source of the issue.
The study examines the scenarios where the magnetic moment and the center of mass of a nanoparticle are misaligned, creating a tandem nanoparticle. The paper investigates the effects of an alternating external magnetic field on such nanoparticles, focusing on specific motion patterns that can be utilized to control the position and velocity of the particles. For this study, relevant literature on nanotechnology in the medical field was reviewed from sources like Scopus, Google Scholar, ResearchGate, and other research platforms.

Keywords: *tandem magnetic nanoparticles, magnetic field manipulation, targeted drug delivery, hyperthermia treatments, diagnostic imaging, biomedical applications.*

Introduction

In recent decades, science and medicine have made tremendous progress in the field of nanotechnology and their application in various fields. One of the most promising areas that is actively developing is medicine, especially in the field of targeted drug delivery [1–2], diagnosis of diseases [3–4], and direct treatment [5]. In this context, magnetic nanoparticles deserve special attention.

Magnetic nanoparticles are nanoscale particles with magnetic properties. Their feature is the ability to respond to an external magnetic field, which allows you to control their movement and behavior in the body. This opens up new perspectives in drug delivery and disease diagnosis [6].

The use of magnetic nanoparticles in medicine has several advantages. First, they can be used to improve drug delivery. By functionalizing magnetic nanoparticles with drug molecules and targets, they can be directed to a specific location in the body, ensuring accurate and efficient delivery of drugs. This allows you to reduce the doses of drugs, reduce their side effects and increase the effectiveness of treatment.

Secondly, magnetic nanoparticles can be used in the diagnosis of various diseases. By functionalizing nanoparticles with markers and antitumor antibodies, they can be used to detect and visualize tumor cells and other pathological changes. This allows for earlier diagnosis and accurate determination of the lesion site, which contributes to more effective and timely treatment [6].

The use of magnetic nanoparticles in medicine is not limited only to drug delivery and diagnostics. Modern research shows that these amazing nanomaterials can also be used for the direct treatment of various diseases. With their help, new prospects in the field of nanomedicine are opening up, allowing for more accurate and effective treatment of pathologies. The size and properties of magnetic nanoparticles can be adjusted so that they can be transported through blood vessels and concentrated in the right areas of the body under the influence of a magnetic field [10].

One of the main applications of magnetic nanoparticles is hyperthermic therapy. When using specially designed nanoparticles that can be heated under the influence of a magnetic field, it is possible to achieve a localized increase in temperature in a certain area of the body. This is used to destroy tumor cells or inactivate pathogens, which makes hyperthermic therapy a promising method of treating cancer and infectious diseases [7].

In this paper, we consider the case when the magnetic moment and the center of mass of a nanoparticle do not coincide (a tandem nanoparticle), which corresponds to a two–cluster nanoparticle, one of which is magnetic, the second is a carrier of the therapeutic component (Figure 1). The influence of an alternating external magnetic field for this case allows us to consider specific cases of motion that can be used to control the position and velocity of particles.

MATERIALS AND METHODS

One of the key aspects of the use of magnetic nanoparticles in medicine is their ability to control in an external magnetic field. This makes it possible to direct, move and control the behavior of nanoparticles in the body, which opens up new opportunities in targeted drug delivery and direct treatment of diseases.

Magnetic nanoparticles have a magnetic moment that allows them to interact with magnetic fields. Under the influence of an external magnetic field, nanoparticles can move, group or separate, depending on their size, shape and magnetic properties. This allows you to control their movement and location in the body [8–9].

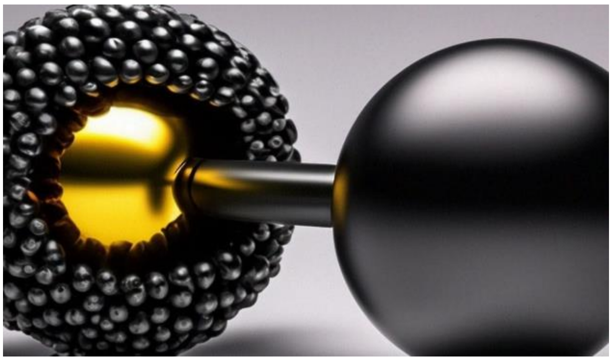

Figure 1. A tandem nanoparticle

Various methods are used to control magnetic nanoparticles. One of them is the use of permanent magnets, which create a permanent magnetic field in the desired area of the body. Nanoparticles with magnetic properties will move in accordance with the lines of magnetic field forces, allowing them to be precisely directed to the target locations [8–9].

Another way to control magnetic nanoparticles is the use of an alternating magnetic field. In this case, electromagnets or systems with an alternating magnetic field are used, which can create magnetic fields that change over time. This makes it possible to control the movement and behavior of nanoparticles by adjusting the parameters of the magnetic field, such as strength, direction and frequency [8–9].

The equation of motion of magnetic nanoparticles in an external magnetic field can be described using the following equation [13–14]:

$$m \cdot \frac{d\vec{v}}{dt} = \vec{F}_M + \vec{F}_d, \quad (1)$$

where: *m* is the mass of the nanoparticle; $\vec{v}$ is the velocity vector of the nanoparticle; *t* is the time; $\vec{F}_M$ is the force caused by the interaction of the nanoparticle with an external magnetic field; $\vec{F}_d$ is the resistance force of the medium in which the nanoparticle is located.

Power $\vec{F}_M$ depends on the properties of magnetic nanoparticles and the magnetic field in which they are located. Next, we will consider the influence of an external magnetic field on a particle with a magnetic moment. When such a particle is placed in an external magnetic field with magnetic induction in $\vec{B}$, the force $\vec{F}_M$ can be calculated, acting on it as a whole, using the following formula [12]:

$$\vec{F}_M = \vec{\nabla}\left(\vec{\mu} \cdot \vec{B}\right), \quad (2)$$

where: $\vec{\mu}$ is magnetic moment of the nanoparticle.

The resistance force of the medium $\vec{F}_d$ can be described by Stokes' law for small particles [11]:

$$\vec{F}_d = 6\pi\eta\vec{r}\upsilon, \quad (3)$$

where: η is viscosity of the medium; $\vec{r}$ is nanoparticle radius.

Moment of force $\vec{M}$, acting on a magnetic nanoparticle in an external magnetic field with magnetic induction $\vec{B}$, is represented by an expression that is analogous to the expression for the moment of forces acting on a small electric dipole in an external electric field with intensity $\vec{E}$ [12]:

$$\vec{M} = \vec{\mu} \times \vec{B}. \quad (4)$$

The moment of force determines the direction of the moment of momentum $\vec{L}$, associated with the magnetic moment:

$$\frac{d\vec{L}}{dt} = \vec{M}, \quad (5)$$

$$\vec{L} = \alpha\vec{\mu} + \vec{L}_0, \quad (6)$$

where: α is gyromagnetic factor; $\vec{L}_0$ is the angular momentum of the attached particle.

The moment of forces turns to zero if the vectors $\vec{B}$ and $\vec{\mu}$ (magnetic moment) parallel (or antiparallel), that is, when the magnetic moment is directed strictly along the external magnetic field or strictly against it. With a small deviation of the vector $\vec{\mu}$ depending on the direction of equilibrium (when the equilibrium state has been reached), the resulting moment of forces has a "returning" character and, in a harmonic approximation, is proportional to the angle of deviation [12].

The equation of motion of magnetic nanoparticles can be solved by numerical methods, taking into account the initial conditions, the external magnetic field and the properties of the nanoparticle. This makes it possible to predict and control their movement and behavior in the body to achieve desired goals, such as targeted drug delivery or localized effects on tumors and pathological areas [10].

RESULTS AND DISCUSSION

The equation of motion in this article provides for conditions under which the direction of the magnetic field changes. The strength of the resistance of the medium is not taken into account. Three scenarios were considered:

a) the value of the inhomogeneous field is constant;

b) the value changes according to the law of *sinsin wt*, the direction does not change in time;

c) the value and direction of the field changes in time according to a harmonic pattern.

When the field is constant in time, the parallel arrangement of the field and the moment give motion in a straight line (Figure 2). Depending on the angle between the vectors of the field and the moment, a trajectory of different intensity is rotated (Figure 3–5).

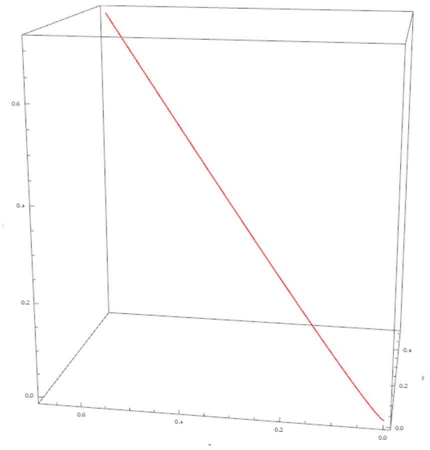

Figure 2. $B_0 = 10$, $m = 0.02$, $a = 0.05$

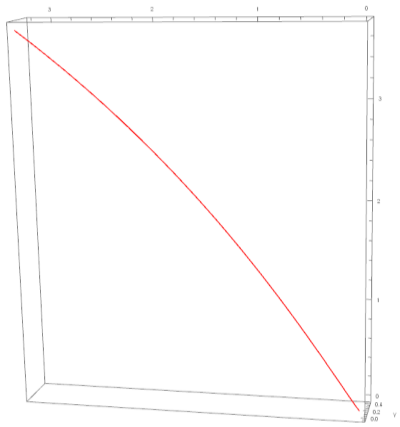

Figure 3. $B_0 = 50$, $m = 0.02$, $a = 0.05$

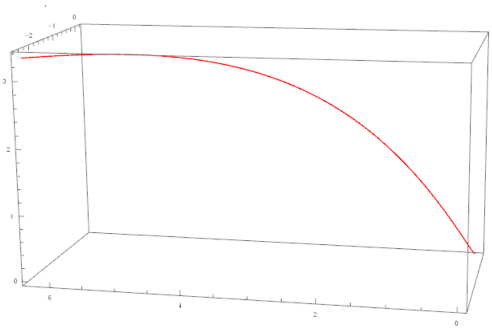

Figure 4. $B_0 = 100$, $m = 0.02$, $a = 0.05$

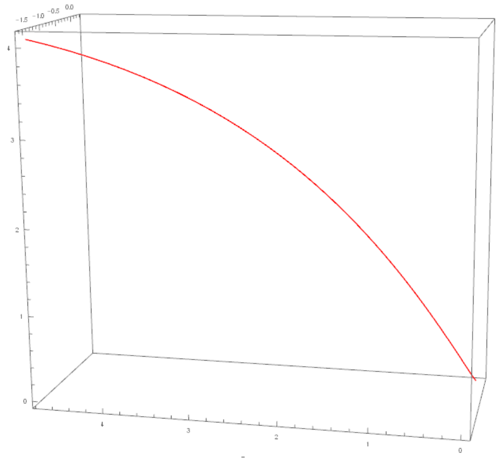

Figure 5. $B_0 = 75$, $m = 0.02$, $a = 0.05$

In a constant field, there is no difference in the trajectories of a simple magnetic nanoparticle and a tandem one, the motion is flat (Figure 6–8)..

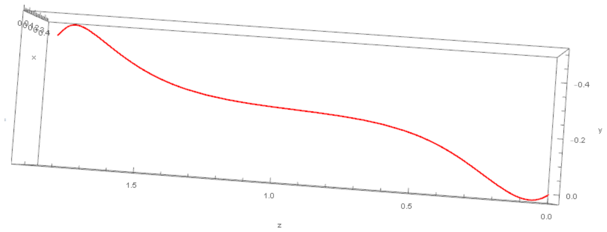

Figure 6. $B_0 = 3000\ sin[w_1 t]$

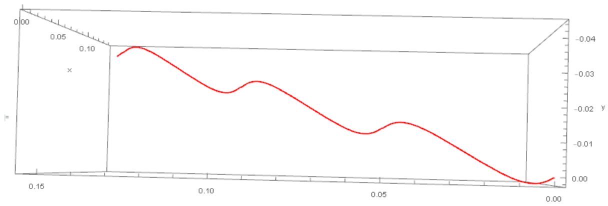

Figure 7. $B_0 = 3000\ sin[2wt]$

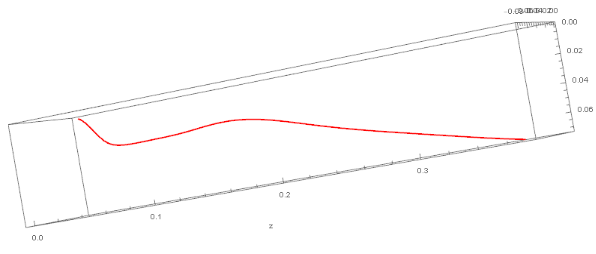

Figure 8. $B_0 = 3000\ sin^2[wt]$

In the case of an alternating field of constant direction, a feature of the movement of a tandem particle appears, consisting in a phase lag (Figure 9).

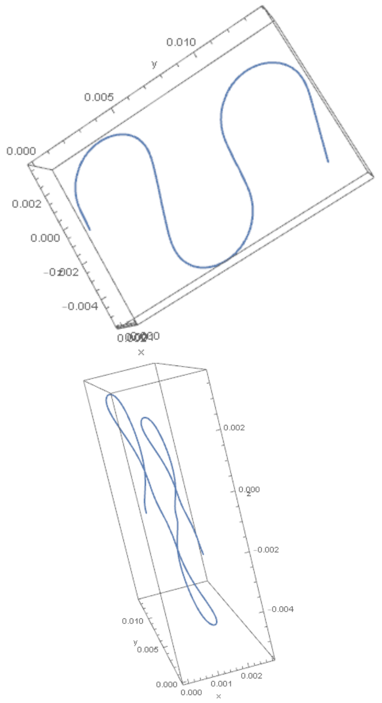

Figure 9. $B_{0x} = 3000\ sin[w_1 t]$; $B_{0y} = 4000\ sin[w_2 t]$; $B_{0z} = 5000\ sin[w_3 t]$

If all three components change, the trajectory becomes spatial, and the movement depends on the type of functions. In this case, the combination of frequencies (w_1, w_2, w_3) gave a sinusoid or spiral. The peculiarity of the motion is determined by the specifics of the rotation of a tandem magnetic particle under the action of a moment of forces.

CONCLUSION

The research focuses on studying how changes in the magnetic field over time affect the behavior of tandem magnetic nanoparticles. By manipulating magnetic induction, it becomes possible to control and direct the movement of nanoparticles. This control method has its advantages in the case of taking into account the resistance of the medium, which we will consider in the following works.

Numerical methods were employed to solve the equation of motion for magnetic nanoparticles, considering various factors like initial conditions, external magnetic fields, and nanoparticle properties. Through this approach, we can anticipate and regulate the movement and actions of these nanoparticles within the body, aiming for specific objectives such as targeted drug distribution or localized effects on tumors and other pathological regions. In addition, understanding the properties and behavior of magnetic nanoparticles can lead to the improvement of materials and technologies, which will allow the development of innovative applications for the development of medicine.

Overall, this study contributes to the ongoing study of magnetic nanoparticles and their potential applications by providing valuable information about their behavior and offering opportunities for developing new strategies for manipulating and controlling nanoparticles.

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АЙНЫМАЛЫ МАГНИТ ӨРІСІНДЕГІ МАГНИТТІК НАНОБӨЛШЕКТЕР ТАНДЕМІНІҢ ҚОЗҒАЛЫСЫ

Н. Ә. Бейсен, Г. Б. Серикахметова, М. Е. Абишев

Әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан

**Байланыс үшін E-mail: nurzada.beissen@kaznu.edu.kz*

Бұл зерттеу мақаласында магниттік нанобөлшектерден тұратын, функционалды нанобөлшектермен көміртекті нанотүтікшелер арқылы байланысқан тандемдік магниттік нанобөлшектердің магнит өрісіндегі уақытша өзгерістердің олардың мінез-құлқына трансформациялық әсері зерттеледі. Магниттік индукцияны манипуляциялау арқылы, нанобөлшектердің електен өткізілген масса центрін және оның осі мен магниттік диполь моменті арасындағы қажетті бұрышты пайдалана отырып, біз мұндай нанобөлшектердің қозғалысын нақты басқара аламыз. Бұл әртүрлі қолданбалар үшін, әсіресе медицина саласында үлкен уәде береді.
Нанотехнология медицина саласында, атап айтқанда наномедицина сияқты кең ауқымды қолданбаларға ие. Кейбір нанобөлшектер жаңа диагностикалық құралдар, бейнелеу әдістері, мақсатты терапия, фармацевтика, биомедициналық имплантаттар және тіндік инженерия үшін перспективалы болып табылады. Нанотехнология қатерлі ісікке қарсы химиотерапиялық препараттар сияқты уыттылығы жоғары емдеу әдістерін қауіпсіз басқаруға мүмкіндік береді. Оған қоса, киілетін құрылғылар өмірлік маңызды белгілерді бақылай алады, рак клеткаларын анықтай алады және нақты уақытта инфекцияларды анықтай алады. Бұл жетістіктер дәрігерлерге денсаулық жағдайындағы өзгерістердің себептері туралы маңызды ақпаратқа мәселенің көзінен тікелей қол жеткізуге мүмкіндік береді деп күтілуде.
Зерттеу нанобөлшектердің магниттік моменті мен масса центрі дұрыс туралanбаған және тандемдік нанобөлшекті жасайтын сценарийлерді зерттейді. Бұл мақалада мұндай нанобөлшектерге айнымалы сыртқы магнит өрісінің әсерлері зерттеліп, бөлшектердің орналасуы мен жылдамдығын басқару үшін пайдалануға болатын нақты қозғалыс үлгілеріне назар аударылады.
Бұл зерттеуді жүргізу үшін Scopus, Google Scholar, ResearchGate және басқа да ғылыми платформалар сияқты көздерден медициналық саладағы нанотехнологиялар бойынша өзекті әдебиеттер талданды.

Түйін сөздер: *магниттік нанобөлшектердің тандемі, магнит өрісінің өзгерісі, препаратты тікелей жеткізу, гипертермияны емдеу, диагностикалық бейнелеу, биомедициналық қолдану.*

ДВИЖЕНИЕ ТАНДЕМА МАГНИТНЫХ НАНОЧАСТИЦ В ПЕРЕМЕННОМ МАГНИТНОМ ПОЛЕ

Н. А. Бейсен*, Г. Б. Серикахметова, М. Е. Абишев

Казахский Национальный университет им. Аль-Фараби, Алматы, Казахстан

**E-mail для контактов: nurzada.beissen@kaznu.edu.kz*

В данной исследовательской статье рассматриваются тандемные магнитные наночастицы, состоящие из магнитных наночастиц, связанных с функциональной наночастицей углеродной нанотрубкой, и исследуются преобразующее влияние временных изменений магнитных полей на их поведение. Манипулируя магнитной индукцией, используя просеянный центр масс таких наночастиц и необходимый угол между ее осью и магнитным дипольным моментом, мы можем осуществлять точный контроль над движением таких наночастиц. Это открывает огромные перспективы для различных приложений, особенно в области медицины.
Нанотехнологии имеют широкий спектр применения в области медицины, особенно в наномедицине. Некоторые наночастицы перспективны для новых диагностических инструментов, методов визуализации, таргетной терапии, фармацевтических препаратов, биомедицинских имплантатов и тканевой инженерии. Нанотехнологии позволяют более безопасно применять высокотоксичные методы лечения, такие как химиотерапевтические препараты от рака. Кроме того, носимые устройства могут отслеживать жизненные показатели, обнаруживать раковые клетки и выявлять инфекции в режиме реального времени. Ожидается, что эти достижения предоставят врачам значительно лучший доступ к важной информации о причинах изменений в состоянии здоровья непосредственно из источника проблемы.
В исследовании рассматриваются сценарии, в которых магнитный момент и центр массы наночастицы не совпадают, образуя тандемную наночастицу. В статье исследуется влияние переменного внешнего магнитного поля на такие наночастицы, уделяя особое внимание конкретным моделям движения, которые можно использовать для управления положением и скоростью частиц.
Для проведения данного исследования была проанализирована актуальная литература по нанотехнологиям в медицинской сфере из высокорейтинговых журналов.

Ключевые слова: *тандем магнитных наночастиц, манипуляция магнитного поля, направленная доставка лекарств, лечение гипертермией, диагностическая визуализация, биомедицинские применения.*