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PONDEROMOTIVE ACTION OF ELECTROMAGNETIC FIELD ON FERROMAGNETICS IN THE CONDITIONS OF MAGNETIC RESONANCE

04.01.11 physics of magnetic phenomena

Abstract

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The dissertation can be found in the library of the Physics Department of Moscow State University.

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Scientific Secretary of the Specialized Council Candidate of Physical and Mathematical Sciences

T.M. KOZLOVA

RELEVANCE OF THE TOPIC

Recently, much attention has been paid to the study of the properties of magnetically ordered substances in various electromagnetic and magnetic fields. This is directly related to the wide possibilities of their practical use, as well as to the variety of interactions arising in connection with this, which are of interest to the theory. Of particular interest in this regard is the case of nonlinear ferromagnetic resonance (NFMR) on unfixed specimens with translational and rotational degrees of freedom.

Numerous experimental and theoretical studies conducted earlier in the field of NFMR have revealed its fine structure taking into account various types of interactions - magneto elastic, exchange, parametric, etc. Some features of this structure have already received quite a satisfactory explanation. The reasons for the appearance of others (slow pulsations of the NFMR signal, spontaneous hopping from one acoustic mode to another, the hysteresis of the magneto acoustic resonance (MAR), and the absorption lines across the field) have not yet been fully clarified. Their elucidation is complicated by the presence of a large number of factors in FMR that influence the experimental results (temperature effects, spurious amplitude and frequency modulations, in homogeneities of magnetic fields, etc.). Usually, NFMR features are interpreted on the basis of the model of excitation of magneto elastic oscillations due to modulation of the exchange and dipole interactions from the lattice side. In turn, the elastic forces caused by magneto striction lead to lattice vibrations.

However, within the framework of such a model and during experiments, the ponderomotive effect of an electromagnetic field on non-fixed samples is usually not taken into account. In the region of resonance, its value increases sharply due to the large Q-factor of the resonating sample system. As a result, it becomes necessary to take into account the translational and rotational degrees of freedom of anisotropic ferromagnets when interpreting the features of NFMR. The significance of ponderomotive forces and moments of forces arising under NFMR conditions, the resonant nature of their dependencies on spatial coordinates and angles in the case of inhomogeneous magnetic fields and anisotropic samples are of interest not only to explain the observed features of NFMR, but also to solve applied problems of macroscopic electrodynamics.

TARGET OF THE WORK

The study of those features of NFMR and MAR in unfixed samples, the occurrence of which can be most strongly influenced by the ponderomotive effect of the electromagnetic field.

Calculation and analysis of expressions for ponderomotive forces and moments of forces acting on a ferromagnet at resonance, in the case of weakly inhomogeneous fields, isotropic and anisotropic samples, taking into account the parametric dependence of the magnetic resonance frequency on spatial coordinates and angles.

Analysis of the possibilities of using the ponderomotive resonant action of an electromagnetic field on ferromagnets for solving a number of technical and fundamental problems of macroscopic electrodynamics.

SCIENTIFIC NOVELTY

In this paper, for the first time, a series of ponderomotive effects was experimentally discovered under conditions of nonlinear ferromagnetic resonance on unfixed samples. Their influence on the appearance of some peculiarities of NFMR and MAR - low-frequency pulsations of the amplitude of the reflected wave from the resonator and intensities of the MAP spectral lines, hysteresis of excitation of magnetoelastic oscillations and absorption lines along the field, etc.

Expressions for ponderomotive forces and moments of forces acting on a ferromagnet at resonance are obtained and analyzed. The calculations were performed taking into account the dependences of the natural frequency of the sample on the translational and rotational degrees of freedom. The cases of weakly inhomogeneous magnetic fields (constant and variable), isotropic and anistropic samples are considered. The physical causes of the magnitude of the magnitude of the ponderomotive effect in FMR have been elucidated.

The possibility of the emergence of stable states of motion of macroscopic spin particles — magnetic dipoles under conditions of magnetic resonance — was experimentally and theoretically shown for the first time. The problem of two interacting magnetic dipoles with regard to their spins is considered. It is shown, with appropriate assumptions, the possibility of the absence of a collapse in such a system and the occurrence of discrete orbits of motion in the case of resonance.

The case of resonant electromagnetic pressure at FMR (analogue of the resonant light pressure) is considered.

SCIENTIFIC AND PRACTICAL VALUE

The results obtained in the work can be used for further studies of the excitation of magnetoelastic oscillations with FMR, for the development of a general theory of the stability of systems of interacting particles with magnetic dipole moments and spins, as well as for testing various expressions of ponderomotive forces in macroscopic electrodynamics, in particular, measuring the Abraham force .

The ponderomotive effect of the electromagnetic field on ferromagnetics with FMR can be widely used in measurement and control techniques - the construction of absolute highly sensitive microwave field sensors (its strength, frequency, polarization, inhomogeneity), the development of direct methods for recording ferromagnetic resonance, and the creation of magnetometers.

APPROBATION OF WORK

The results of the work were reported at the plenary session of the All-Union Conference on the Physics of Magnetic Phenomena (Kharkov, 1979), at the seminars of the institutes of the AN SSSR - the IFM UNC (Sverdlovsk, 1976), the IAE named after I. V. Kurchatov (Moscow, 1978), FTI named after A. F. Ioffe (Leningrad, 1979), MI named after V. A. Steklov (Moscow, 1979), Mechanics of Moscow State University (Moscow, 1980), FI named after P. N. Lebedeva (Moscow, 1981), Moscow State University named after M. V. Lomonosov (Moscow, 1982), outlined in 9 published scientific papers.

WORKLOAD

The work consists of introduction, four chapters and general conclusions. It is presented on 109 pages of typewritten text, contains 24 figures, 2 tables and a list of references from 111 titles.

THE CONTENT OF THE WORK

The thesis consists of an introduction and four chapters, general conclusions and bibliography. After each chapter are private conclusions.

The introduction discusses the relevance of the chosen topic. Formulated goal of the work. The structure and content of the thesis by chapters.

Chapter I, which is a literature review, analyzes the current state of theoretical and experimental studies of nonlinear ferromagnetic resonance on loose samples, especially its anomalies. Much attention is paid to the work separately, considering the ponderomotive effect of the electromagnetic field on sample resonators in the low-frequency, optical, VCH and microwave wavelength ranges. Unclear, controversial and unresolved issues are noted, the specific tasks of the thesis are set.

Chapter II is devoted to the experimental study of NFMR and MAR on loose samples.

In § 1 of the chapter, the scheme of the assembled setup and the experimental conditions are signed. Monocrystals of iron – yttrium garnet (YIG) in the form of spheres were used as samples. Four specimens with a diameter of d = 1.34; 0.97; 0.775; 0.41 mm and a line width of 2△H = 0.23; 0.49; 0.55; 0.56 Oe, respectively. During measurements, the samples were placed in the center of the H_{102} resonator, where there was no heating of the ferromagnet, due to the electric components of the microwave field. The intrinsic Q factor of the resonator was 10^3. Observation of the spatial movements of the samples during the experiment was carried out through out-of-band protective waveguides and correlated in time with the moment of appearance of distortions in the shape of the NFMR line and the excitation spectrum of the MAR. When registering NFMR, the samples were freely placed in a quartz ampoule vertically or horizontally located relative to the direction of gravity, or fixed in polystyrene or fluoroplastic.

The required magnitude of the magnetic field was provided by a permanent magnet and two pairs of modulation coils. The modulation coils made it possible to vary the magnitude of the field in the range from 3.110 Oe to 3.450 Oe, taking into account the frequency of the used magnetron generator 9.420 MHz and a possible change in the resonant field value during spatial displacements and rotations of anisotropic YIG samples. The heterogeneity of the field of the permanent magnet, after appropriate processing and polishing of the pole pieces, in the central region was less than 2 Oe/cm. The absolute measurement error of the magnetic field did not exceed 0.5 Oe. The sweep across the field was adjusted smoothly from 0 to 150 Oe. The dynamic range across the field was automatically provided by applying a linearly varying voltage to the field control system from the NGPK-ZM generator, or from the generator, developed by the author, with a sweep time of 0.01 s and more, as well as manually.

The power of the microwave oscillations was regulated by a smoothly polarized attenuator from 0 to 5 W. The power measurement error was 5%. A ferrite circulator was used to prevent the effect of magnetron frequency pulling.

The absorption line was recorded on a two-coordinate self-recording potentiometer PDS-021M under conditions of adiabatic slow passage through the field and in the mode of continuous transverse ponderomotive. For averaging, the line was recorded several times under the same conditions. With a sweep time of less than 1 s, the absorption line was recorded on a C8-9A oscilloscope. Investigation of the character of excitation of MAR was carried out using a 3 cm IV-66 spectrum analyzer, a C1-54 high-frequency oscilloscope, and an CHZ-35A frequency meter. The recording of low-frequency pulsations of the amplitude of the reflected wave from the resonator and the amplitude of the magneto elastic oscillations was corrected using a low-frequency oscilloscope C1-4, frequency meter F599 and spectrum analyzer IV-66.

In § 2 of Chapter II, the ponderomotive effects, which were found when observing the NFMR on loose samples, are described. When scanning across the field, slow spatial movements of the sample were found. Simultaneously with the onset of sample movement, the appearance of anomalies in the shape of the absorption line and the excitation spectrum of the magneto acoustic resonance (low-frequency pulsations of the amplitude of the reflected wave, intensities of spectral lines; their breakdown; hopping from one acoustic mode to another) was observed. Typical graphs of the amplitude of the reflected wave from the resonator are shown in Fig. 1. An increase in the power from 0.04 W, at which displacements were observed, to 0.15 W and above led to complex sample movement, low-frequency oscillations, on the inner surface of the ampulla cavity. At power P = 2W, the intensity of its movements increased sharply and, ultimately, it was pushed out of the resonator in the quartz tube. Sometimes short-term levitation of the sample was observed. Then the pattern swung and fell down.

Complicated trajectories of motion occurred when the sample was placed at the bottom of the resonator (P = 0.08 W). An increase in power up to 2 W led to the closure of the trajectory of movement into a circle with a diameter of ~ 8 mm around the center of the resonator.

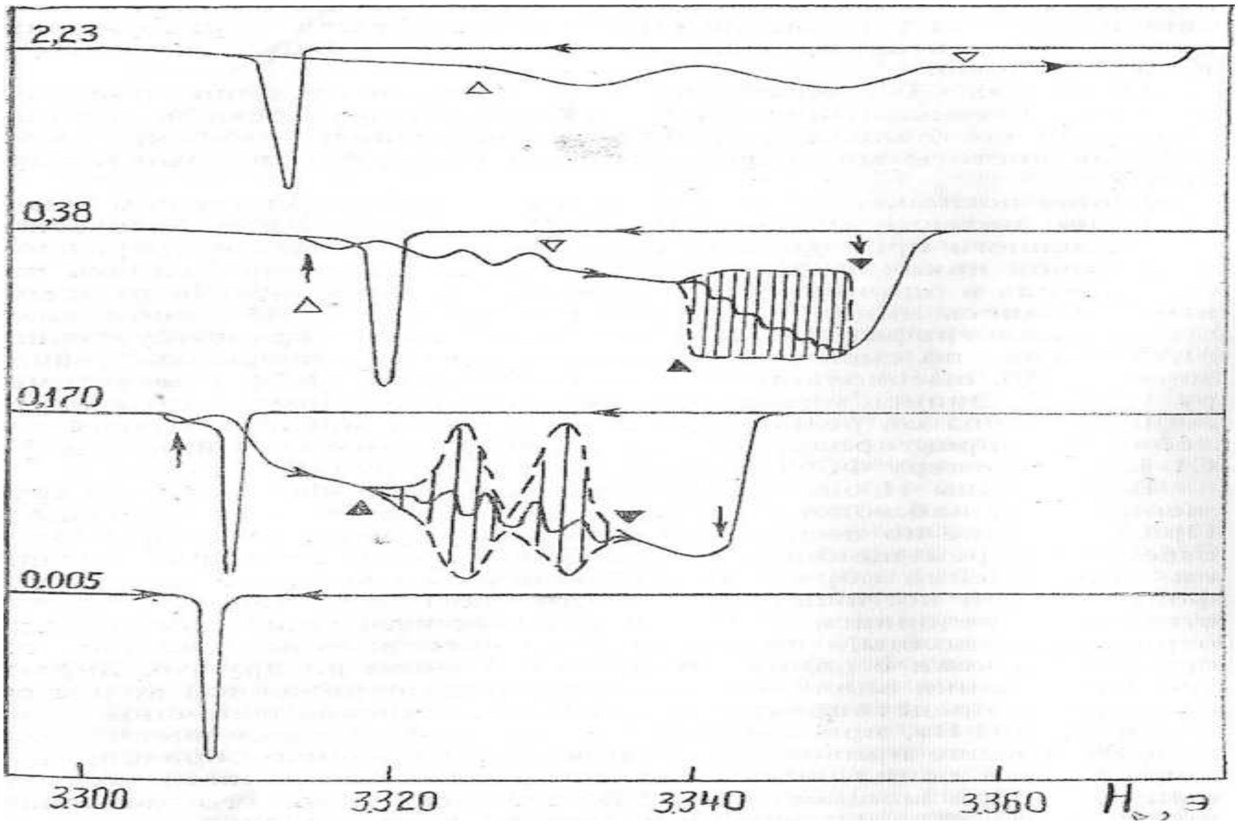

Fig. 1 Dependence of the amplitude of the reflected wave on H_0 at various pump power levels in W, d = 0.775 mm, 2△H = 0.55 Oe, the sweep speed is 8 Oe/s, ⇅ - areas of MAR arousal and ▲▼ (△▽) – LF -pulsations of absorption lines and MAR with ν^{lf}=9-20 Hz (3-0.7 Hz), ⇆ - field sweep direction.

Additional research has shown that magneto elastic oscillations and self-heating of the sample at resonance are not the causes of its spatial displacements. The magnitude of the ponderomotive force F arising at resonance was estimated from the separation of two spherical YIG samples from each other (P = 0.5 W). This experience has shown that, compared with the magnitude of the force of gravity FT, which is a natural standard for experiments with loose samples, its value exceeds FT, at least 120 times. It was found that the direction F depends on the frequency offset. From the side of the less resonant fields, the attraction of the samples to each other was observed, from the side of the fields more resonant - repulsion.

In § 3 of Chapter II, the results of studies of the characteristics of the NFMR and MAR are given. The graphs of the absorption line shape and hysteresis magnitude across the field from the pump power level for loose and fixed samples, the frequency of elastic oscillations MAR from the magnetic field strength at different pump power levels, the dependence of the absorption line shape on the sweep rate across the field are presented.

The detection of spatial movements of the samples made it possible to distinguish between low-frequency pulsations of the NFMR and MAR signals into two types. The frequency of the first pulsations increased from 9 to 20 Hz with an increase in the pump power. At the same time, quasi-peridic movements were observed in the hemisphere of a tube cavity. The second type of low-frequency pulsations was detected at a power of $P \approx 0.3$ W. Their frequency, in contrast to the first, with increasing pump power decreased from 3 Hz to tenths of a Hertz. An increase in the pump power led to a decrease in the excitation region across the field of LF -pulses of the 1st type and an increase in the excitation region of the LF -pulsations of the 2nd type (Fig. 1). The excitation of the low frequency pulsations of the 2nd type was not accompanied by the movement of the sample. It was found that a sharp increase or decrease in the sweep speed as compared with a speed of about 10 Oe/s led to the disappearance of the excitation of low-frequency pulsations and a change in the shape of the resonance absorption curve. An increase in the magnetic field gradient at the sample location to 9 Oe/cm led to the excitation of type 1 LF-pulsations and MAR at lower power levels.

The fixation of the sample in polystyrene and fluoroplastic caused a breakdown of MAR excitation, a sharp decrease in the field hysteresis, a change in the direction and magnitude of the hysteresis depending on the orientation of the samples relative to the external constant magnetic field. Typical graphs of the dependences of the amplitude of the reflected wave on the resonator for fixed samples are shown in Fig. 2.

§ 4 of Chapter II is devoted to a discussion of the results of the study of the features of the NFMR and MAR.

It is shown that taking into account the ponderomotive effect of the electromagnetic field on non-fixed anisotropic samples under conditions of magnetic resonance allows us to explain many features of NFMR and MAR. Its significant value and the nature of the dependence on the detuning in the field are explained by the parametric resonance dependence of the magnetization of the anisotropic sample on the coordinates and angles.

The influence of the translational and rotational degrees of freedom of the samples on the appearance of slow variations of the NFMR and MAR signals of the low-frequency pulsations of the l-ro type is considered. It is shown that their appearance can be explained by the violation of resonant conditions as a result of the parametric dependence H^{rez} $[(\mathbf{H}_a(\mathbf{r}),\angle(\mathbf{H}_0, \mathbf{H}_a)]$ when the sample moves in a non-uniform magnetizing field $\mathbf{H}_0$ and when it turns under the action of forces and moments in FMR conditions (here $\mathbf{H}_a$ – anisotropy field. The estimates of the frequency of spatial oscillations of the sample and its dependence on the pump power are given, which give good agreement with the experimental data.

A mechanism for the excitation of LF-pulsations of the 2nd type is proposed, taking into account the heating of the sample due to the microwave power absorbed during resonance. It is shown that heating of the sample leads to the appearance of conditionally nonlinear phenomena — such as thermal LF pulsations of the 2nd kind in NFMR as a result of the dependence $H^{rez}[H_a(T)]$, where T is the temperature. The calculated values of the frequency of the low-frequency pulsations based on the thermal model and the nature of its dependence on the pump power are confirmed by experimental data.

It is noted that the simpler excitation of low-frequency pulsations at scanning speeds of the order of 10 Oe/s can be explained by the synchronism of its magnitude with the parameters of the thermal and mechanical inertness of the YIG samples ~ $2\Delta H/\tau^{lf}$ where τ^{lf} is the time characterizing the inertia of heating, or displacements of the ferrite. The causes of hysteresis phenomena of NFMR and MAR on loose and fixed samples of YIG are analyzed.

In addition to the two previously known mechanisms of hysteresis (due to shape anisotropy and the dependence $H^{rez}\{H_a[M_z(H_1)]\}$, where H_1 is the amplitude of the pump field, M_z is the Zth component of magnetization, $\mathbf{H}_0\uparrow\uparrow\mathbf{OZ}$), the contributions from the self-heating of the sample $H^{rez}(H_a,H_0)$ and from its spatial displacements No.^{ez}- (H_a,H_0). Taking them into account allowed us to explain the experimental data on hysteresis for fixed and non-fixed samples - YIG single crystals. A model is proposed for the excitation of magnetoelastic oscillations based on the ponderomotive effect of an electromagnetic field in FMR.

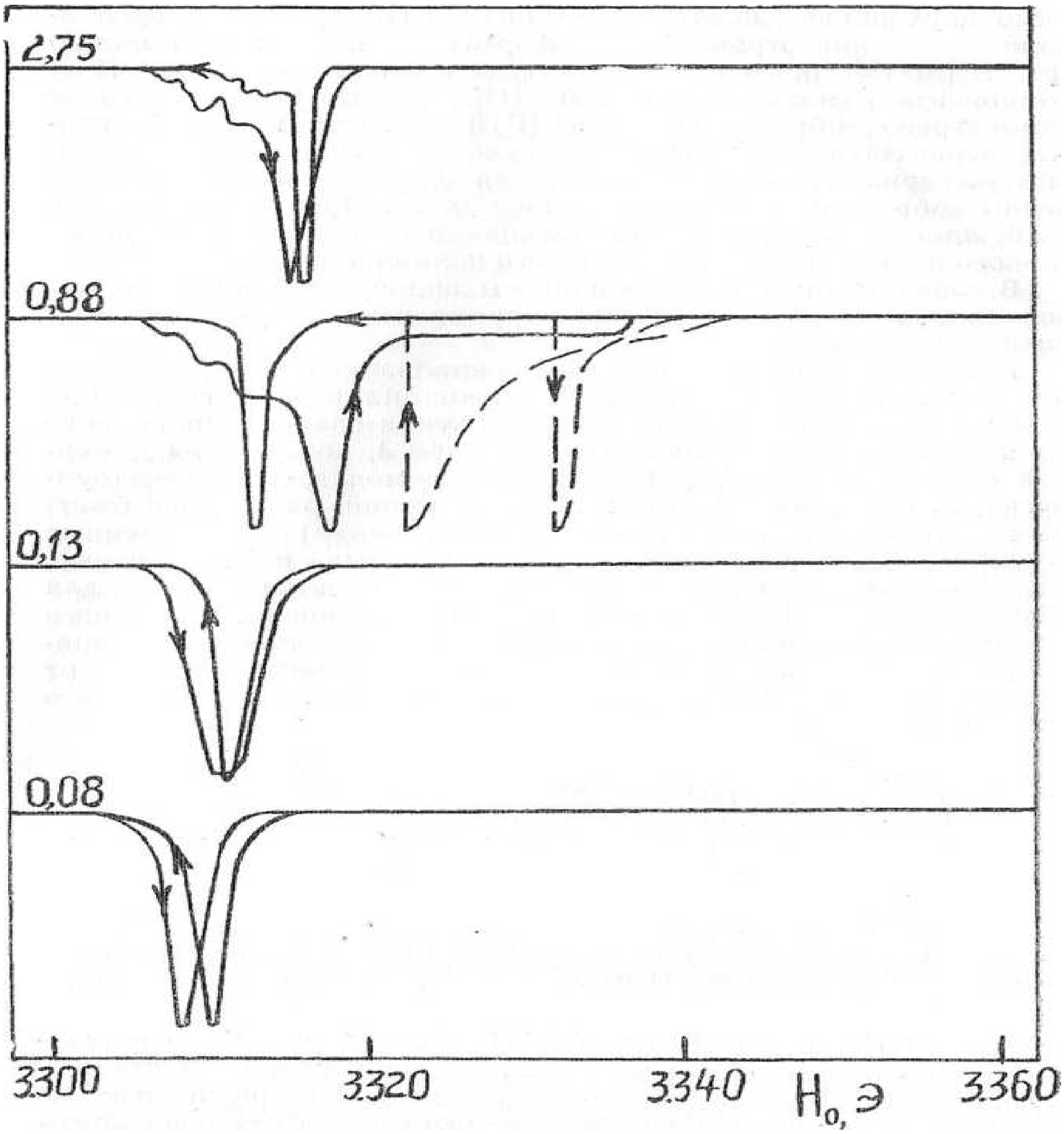

Fig. 2. The dependence of the amplitude of the reflected wave on $\mathbf{H_0}$ at various pump power levels in watts. The sample with d = 0.775 mm, 2△H = 0.55 Oe is fixed with glue, ⇆ - field sweep direction? sweep speed 8 Oe/s, - - - the sample is rotated through a test angle ~ π/3.

Chapter III deals with the issues of the ponderomotive effect of an electromagnetic field on ferromagnets under conditions of magnetic resonance.

In § 1 of Chapter III, an expression for the ponderomotive force acting on a ferromagnet at resonance is obtained and analyzed. The problem was solved in the approximation of a weakly inhomogeneous field $|\mathbf{gradH}_{0,1}| << \Delta H/d$, magnetostatics $d<<\lambda$, lack of domain structure $4\pi M_0/3<<\Delta H_0$, thermal self-heating, magnetoelastic, nonlinear exchange interactions, separation of fast (UHF) and slow (mechanical) variables $\omega^{lf}/\omega^{uhf}<< <<1$ and based on the Abraham and Minkowski tensors, where M_0 is the saturation magnetization, and λ is the wavelength for microwave oscillations. Calculations have shown that under conditions of magnetic resonance, the main contribution comes from the terms due to the parametric resonance dependence of the magnetization on the coordinates, taking into account the inhomogeneities of alternating and constant magnetic fields:

$$f_{i,1}^{A,M} \simeq \frac{\omega_0 \omega_1 (\omega_r^2 + \Delta\omega^2)}{(\omega_1^2 + \omega_r^2 + \Delta\omega^2)^2} M_0 \nabla_i H_1 \qquad (1)$$

$$f_{i,}^{A,M} - \frac{2}{(\omega_1^2 + \omega_r^2 + \Delta\omega^2)^2} M_0 \nabla_i H \qquad (2)$$

where $\omega_0 = |\gamma| H_0$, $\omega_1 = |\gamma| H_1$, $\omega_r = |\gamma| \triangle H$, $\triangle\omega = \omega - \omega_0$, γ - gyromagnitty ratio. The graphs of the dependences of the corresponding terms on the frequency detuning are given for different amplitudes of the pump field. The obtained expressions for the ponderomotive force allowed us to explain the magnitude and nature of the ponderomotive effects found during NFMR. It is shown that the maximum value of the force acting on a ferromagnet under magnetic resonance conditions, as in the previously considered problems of the ponderomotive effect of waves on resonators (samples), is proportional to the quality factor of the resonating system — the YIG sample ($H^{rez}/\triangle H$).

In § 2 of Chapter III, the remaining term in the expression of the ponderomotive force $\Delta f = -\,\mathbf{rot}[\mathbf{M} * \mathbf{H}]/2$ is considered. It is shown that for ferromagnets this term is by no means small, as previously thought, and can be detected under magnetic resonance conditions ($\Delta f \approx M_0 \mathrm{grad} H_{0,1}$) The problem was solved for an isotropic single-domain sample placed in a weakly inhomogeneous magnetic field. The physical meaning of this term has been clarified in the case of FMR, an analogue of electromagnetic resonant pressure in optics.

In § 3 of Chapter III, expressions for the moment of forces acting on an isotropic and anisotropic sample of a ferromagnet at resonance are obtained. Graphs of the dependences of the moment of forces on the frequency detuning are given for different amplitudes of the pump field for isotropic samples and on orientation angles with respect to an external magnetic field for anisotropic ones. In the case of anisotropic media, the problem was solved for a nonconducting, single-domain spherical sample of a ferromagnet of a cubic syngony placed in a uniform magnetic field. The corresponding expressions for the moments of forces are:

$$\mathcal{N}_u \simeq \frac{\omega_1 \omega_r}{\omega_1^2 + \omega_r^2 + \Delta\omega^2} \mu_0 H_1 \qquad (3)$$

$$\mathcal{N}_a^{\theta} \simeq -\frac{10\omega_0 \omega_1^2 \Delta\omega}{(\omega_1^2 + \omega_r^2 + \Delta\omega^2)^2} \sin 2\theta (2\cos 2\theta + \sin^2\theta \sin^2 2\varphi) \mu_0 H_a \qquad (4a)$$

$$\mathcal{N}_a^{\varphi} \simeq -\frac{10\omega_0 \omega_1^2 \Delta\omega}{(\omega_1^2 + \omega_r^2 + \Delta\omega^2)^2} (\sin^4\theta \sin 4\varphi) \mu_0 H_a \qquad (4б)$$

where $<\theta=<$ ($\mathbf{H}_0$, [**001**]), $<\varphi=<$ ([**100**], (**YOZ**)), $\boldsymbol{\mu}_o$ is the magnetic moment of the sample. It is shown that the maximum magnitude of the moment of forces acting on an ansatropic ferromagnet at resonance is proportional to the quality factor of the sample ($H^{rez}/\triangle H$).. The estimates of the magnitude and nature of the dependence of the moment of forces on the detuning across the field confirmed the need to take it into account when interpreting the hysteresis and ponderomotive effects of NFMR.

In § 4 of Chapter III, an example is considered illustrating the influence of a resonant inhomogeneous electromagnetic field on the stability of the motion of spin particles and explaining the detected motion of a macroscopic spin particle — a spherical YIG in orbit under FMR conditions. First, the motion of a single particle — a magnetic dipole in a resonant inhomogeneous field — was analyzed, and then the self-consistent problem of two dipoles was considered with their spins taken into account. The possibility of the absence of collapse in the system of interacting magnetic dipoles when taking into account their spins and resonant capture has been established.

Chapter IV is devoted to the analysis of the possibilities of using the ponderomotive effect of an electromagnetic field on ferromagnets at resonance.

In § 1 of Chapter IV, the prospects for registering a ferromagnetic resonance by force and moment of forces are considered in comparison with conventional methods. It was shown that, in the case of isotropic samples, the registration by the moment of forces will make it possible to obtain a sensitivity of the order of 10^{11} spins, for anisotropic ~ 10^7 spins.

In § 2 of Chapter IV the possibilities of increasing the sensitivity of absolute ponderomotive electromagnetic field sensors using FMR are analyzed. It is shown that the sensitivity of the ponderomotive wattmeters of the microwave range can be increased by several orders of magnitude compared to the best foreign analogues. The possibility of developing selective, polarization, compact, with high noise immunity on thermal noise, easily tunable sensors of power, frequency, intensity and polarization of an alternating electromagnetic field is noted.

In § 3 of Chapter IV, the possibility of checking the correctness of various expressions for ponderomotive force in macroscopic electrodynamics under FMR conditions is investigated. The most optimal conditions for such experiments have been identified.

In conclusion, general conclusions on the thesis are presented and a plan for further research on the ponderomotive effect of waves on resonators is outlined.

MAIN RESULTS AND CONCLUSIONS

1. The ponderomotive effect of the electromagnetic field (spatial displacement and stable orbital movement of YIG spheres, separation of two samples from each other, etc.) was found with a nonlinear FRM on samples of single crystals of yttrium iron garnet.
2. The anomalies of the NFMR and MAR signals detected (low-frequency pulsations of the amplitude of the reflected wave and intensities of the MAR spectral lines with a frequency of 3 Hz or less, of one type, 9 Hz or more, of the other; excitation hysteresis of the magnetoelastic oscillations and the absorption line in the field; the shape of the absorption line from the sweep time under conditions of adiabatic slow passage through the field) are explained on the basis of taking into account the ponderomotive forces arising in FMR and moments of forces for isotropic and anisotropic samples in inhomogeneous magnetic fields. s, as well as self-heating thermal phenomena in ferromagnets due to the absorbed microwave power. An appropriate model for the excitation of magnetoelastic oscillations is proposed.
3. Expressions for ponderomotive forces and moments of forces acting on a ferromagnet at resonance are obtained and analyzed. The formulas for the force are derived from the Abraham energy-momentum tensor in the case of weakly inhomogeneous fields. Moments of forces are calculated for isotropic and anisotropic ferromagnetic samples, based on the expression for the free energy. The reason for the significance of their magnitudes has been clarified - the high quality factor of the resonant system of a sample of YIG of about 10^4. Considered are the analogue of the resonant light pressure - the resonant electromagnetic pressure with FMR; an example illustrating the effect of a resonant inhomogeneous electromagnetic field on the stability of the motion of spin particles with a magnetic moment, and explaining the detected motion of a macroscopic spin particle — a spherical YIG sample in orbit.
4. The possibilities of using a ponderomotive resonant action of an electromagnetic field on ferromagnets to solve a number of technical (construction of absolute highly sensitive microwave sensors, $P_{min} < 10^{-10}$ W, magpitometers; development of direct methods for recording ferromagnetic resonance with a sensitivity of ~ 10^7 spins) and fundamental problems of macroscopic electrodynamics (measuring Abraham forces, checking various expressions for ponderomotive forces).

5. The analysis of theoretical and experimental work on the ponderomotive effect of waves on resonators (samples) in the low-frequency, optical, high-frequency and microwave ranges, as well as in the field of magnetic resonance, proved the correctness of P. N. Lebedev's statement on the generality of the laws found, regardless of their physical nature - influencing field and the corresponding resonator (substance).

The main results of the thesis are presented in the works:

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6. Shironosov V. G. Slow Sweep Generator. - PTE, 1979, No. 5, p. 151 - 152.
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8. Shironosov V. G. Increasing the sensitivity of ponderomotive wattmeters using ferromagnetic resonance. - Radio engineering, 1980, vol. 35, No. 5, p. 64.
9. Shironosov V. G On the need to take into account the ponderomotive moment of forces when studying nonlinear ferromagnetic resonance in anisotropic samples. - ZHTF, 1981, V. 51, No. 1, p. 192–193.

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