Using of HTS tape coils for the design of a magnetic bearing

E Kurbatova, P Kurbatov, E Kuschenko and Y Kulaev
National Research University «Moscow Power Engineering Institute», Moscow, Russia

E-mail: kurbatovpa@mpei.ru

Abstract. The use of HTS materials for the construction of magnetic bearings has shown their high efficiency. Currently, more and more research is focused on the use of tape superconductors for magnetic bearings. Application of HTS tapes allows simplifying the manufacturing technology of these devices and improving the specific power characteristics. However, when modelling devices with HTS tapes, computational difficulties arise due to the small thickness of the active layer. The paper considers the possibility of using models for magnetization to describe the properties of HTS tapes in the calculation method based on the integral equations of an electromagnetic field. The features of the proposed models are illustrated by the results of solving simple test tasks and calculations of real designs of magnetic bearings. To confirm the correctness of the simulation, the calculation data are compared with the data of experimental studies.

1. Introduction

HTS bulks in form of the ring are usually used for magnetic bearings of rotating mechanisms [1-5]. To create the required radial anisotropy structure, rings are made of the individual sectors. Developing the production of high-quality HTS tapes with significant critical currents has expanded the prospects for improving the design of magnetic bearings. The necessary radial structures can be made of HTS tapes in the form of cylindrical coils [6,7]. The width of the tapes produced by the industry is up to 12 mm. This is sufficient to create the required distribution of induced currents in an open-circuit coil, which determines the force interactions in the bearing. The size of HTS coils with the same currents is much smaller than bulk HTS ring. There is also an opportunity to reduce energy costs for cooling. Coils made of HTS tapes have a higher average critical current density in volume, which can be used to increase the specific force parameters of bearings.

HTS tapes have a thin superconducting layer with a thickness of up to several microns. This feature, along with complex nonlinear and anisotropic properties, causes difficulties in the numerical analysis of magnetic systems with HTS tapes. Methods of modelling elements made of HTS tapes need to be improved. In this paper, we consider the possibility of using the model for magnetization instead of the model for currents for numerical analysis of an electromagnetic field in HTS tapes. The proposed model describes the nonlinear, hysteretic, and anisotropic properties of this material. Application of the model for magnetization allows to perform the calculation as the analysis of a stationary magnetic field, which greatly simplifies the computational procedures. However, this model has certain accuracy limitations due to simplifying assumptions about the real distribution of currents in the tape. The paper presents the results of theoretical and experimental studies of simple examples and real practical problems. The calculated data are compared with previously published experimental results and experimental data obtained by authors.
2. Mathematical models

In HTS tape, these are two structures of current: circuit current structures, which flow in the closed electric circuit, and vortex current structures circulating in local areas. Here we consider only the eddy current, i.e. occurrence of all currents is determined by the law of electromagnetic induction. In a closed-circuit tape, circuit currents along the tape are caused by changes of magnetic flux in the loop and currents with a vortex structure due to variations of the normal component (regarding the surface of the tape) of the magnetic induction vectors. If the tape is open-circuit, the circuit currents are absent and there are only vortex current structures.

In this work, we study the method for modelling an open-circuit HTS coil with several turns. In this case, we have only currents with vortex structure, which can be induced in each turn and created by the radial magnetic field (figure 1). Such coil can be considered and applied in magnetic bearing as an HTS bulk with radial anisotropy.

![Figure 1. Vortex currents in HTS tape: (a) – open-circuit HTS coil; (b) – segment of HTS tape](image)

2.1. Model for magnetization

In simple connected regions, vortex current structures can be represented by their magnetic moments and, accordingly, magnetization \( J = \nabla \times M \). To describe the distribution of the currents in a superconductor the real currents are represented as a distribution of a set of small elementary superconducting hollow thin-walled cylinders distributed in the volume of a superconductor. It is assumed that the diameter of the cylinders is much smaller than the length, and the current density in the wall is limited by critical parameters of material. The magnetization \( M \), in this case, is determined as the density of the magnetic moments of these superconducting cylinders and directed perpendicular to the surface of the tape.

Figure 2(a) illustrates the magnetization curve for superconducting material. If the HTS has been transferred to the superconducting state in the absence of a magnetic field (ZFC), then the magnetization in the initial state is zero (point 0). With an increase of magnetic field strength, the magnetization increases to satisfy the condition of an ideal diamagnetic \( M = -H \) (magnetic induction equal to zero) until reaching point 1. Then the magnetization is limited to a critical values \( M_c(H) \) up to \( M=0 \) at point 3. If the magnetic field strength is reduced (for example from point 2’), then the magnetization will be determined from the condition of the constant magnetic induction \( B_2 \), which is reached at point 2’ – \( M = B_2/\mu_0-H \) until a critical value at point 3’. A further change in magnetization will be determined by critical values \( M_c(H) \) up to point 4’. At field cooling (FC) the magnetization is changed similarly but from the initial point \( H \neq 0 \).

The initial magnetization line and the return lines are linear segments with a constant angle of slope. The limiting loop is formed by the critical magnetization function, determined by formulas

\[
M_c(T,H) = \begin{cases} 
M_{c,\text{max}}(T) \cdot (1 - |H/H_{CM}(T)|^\alpha)^\beta, & \text{if } |H| \leq H_{CM}, \\
0, & \text{if } |H| > H_{CM}, 
\end{cases}
\]

where \( M_{c,\text{max}}(T) \) – the maximum value of the critical magnetization at a given temperature; \( \alpha, \beta \) - model parameters (real positive numbers); \( H_{CM} \) – the critical value of the magnetic field. In figure 2(b), the different limiting contours for critical magnetization are shown, which are obtained with various \( \alpha \) and \( \beta \).

It is assumed that in a certain small volume of the superconductor a sufficiently large number of elements are distributed, the parameters of which obey the probabilistic distribution laws. These parameters include the form of the dependences of the critical magnetization on the magnetic field and temperature, and the spatial orientation of the elementary cylinders. The spatial orientation determines the anisotropic properties of the material. In the case of thin superconducting layer, such as in HTS...
tape, the anisotropy can be considered uniform and all cylinders are oriented perpendicular to the surface of the tape. The volume-averaged magnetization properties of a superconducting material expressed as the dependencies of the magnetization on the magnetic field, are determined by the probabilistic characteristics of the properties of the elementary cylinders (figure 3).

**Figure 2.** Model for magnetization: (a) – the dependence of the magnetization on the magnetic field strength for a homogeneous sample; (b) – limiting contours of the critical magnetization obtained at various $\alpha, \beta$: 1 – $\alpha=1.5, \beta=0.2$; 2 – $\alpha=1.5, \beta=1.0$; 3 – $\alpha=1.5, \beta=2.0$; 4 – $\alpha=1.5, \beta=5.0$.

**Figure 3.** Dependences of the magnetization on the magnetic field strength in different cases: (a) – $M_{C,\text{max}}, H_{CM}$ are homogeneous; (b) – $M_{C,\text{max}}, H_{CM}$ are inhomogeneous.

The proposed model of magnetization relates to approximate mathematical models. This model is intended for a simplified description of the distribution of currents at the macroscopic level instead of the known models for transport currents. Replacing the induced currents with an equivalent distribution of magnetization in the case of HTS tapes makes it possible to reduce the non-stationary problem to the stationary one and simplify the calculation procedures.

The physical basis of modelling HTS tape using magnetization is the same as in the models for current. Only the type of sources describing the induced currents has been changed. Therefore, the parameters of models for current, for example when using the Power Law model [8,9], should be equivalent to the model for magnetization.

For the numerical calculation the concept of piecewise-homogeneous regions for currents is used. It means, that in these regions the properties of material are constant (for HTS there are critical parameters). When using the model for magnetization, discrepancies with the model for currents may appear, because in general case, the model for magnetization cannot be homogeneous. In this paper, we assess the possibility of applying the model of piecewise homogeneous magnetization properties for HTS tapes.

**2.2. Model for currents**

For verification of the proposed model for magnetization, we compare it with the model for currents presented in our previous works [10]. It describes the properties of HTS similarly to Power Law model. This model is based on the nonlinear approximation of the specific resistivity (figure 4(a)):

$$\rho(H,J,T) = 0.5\rho_0 \times \left[1 + \tanh\left[-(1-T/T_C)\cdot(1-|H|/H_C(T))\cdot(1-|J|/J_{C}(T,H))/\delta\right]\right],$$

where $\rho$ and $\rho_0$ – the electrical resistivity in the superconducting and normal states respectively; $J_C(T,H)$ – critical current density; $T$ – temperature, $H$ – magnetic field strength; $H_C(T)$ – critical magnetic field strength, $T_C$ – the critical temperature, $\delta$ – constant coefficient of dispersion.
The dependence of the critical current density on the magnetic field strength is determined by formulas

\[ J_c(T, H) = J_{c,\text{max}}(T) \cdot (1 - |H/H_c(T)|^\alpha)^\beta, \text{ if } |H| \leq H_c, \]

\[ J_c(T, H) = 0, \text{ if } |H| > H_c, \]  

(3)

where \( J_{c,\text{max}}(T) \) – the maximum value of the critical current density at a given temperature; \( \alpha, \beta \) - model parameters (real positive numbers); \( H_c \) – the critical value of the magnetic field. Figure 4(b) shows the dependences of the critical currents density, which are obtained with various \( \alpha \) and \( \beta \).

![Figure 4](image)

**Figure 4.** Model for currents: (a) – the dependence of the specific resistivity on the current density at different temperature: 1 – \( T=85 \text{ K} \); 2 – \( T=80 \text{ K} \); 3 – \( T=75 \text{ K} \); (b) – limiting contours of the critical magnetization obtained at various \( \alpha, \beta \): 1 – \( \alpha=3.0, \beta=1.0 \); 2 – \( \alpha=2.0, \beta=1.0 \); 3 – \( \alpha=1.0, \beta=1.0 \); 4 – \( \alpha=1.0, \beta=2.0 \); 5 – \( \alpha=1.0, \beta=3.0 \).

### 3. Verification of the model

#### 3.1. Comparison with model for currents

The difference between the models for currents and for magnetization is illustrated by the results of solving the following test problem. The task is presented in 2D, thus the open-circuit coil can be approximately represented as a stack of HTS tapes. The stack made of 10 layers of HTS tape is placed in the gap between two permanent magnets with the same directions of magnetization. The width of the tape is 12 mm, the thickness of the superconducting layer is 1.5 \( \mu \text{m} \), the thickness of one tape is 120 \( \mu \text{m} \). The critical current of the tape is \( I_c = 500 \text{ A} \). Dimensions of permanent magnets and their arrangement are shown in figure 5. Magnetization of permanent magnets is 1000 kA/m.

HTS stack is placed in the center of the gap and transferred to the superconducting state at FC. After that, permanent magnets are removed and a trapped magnetic field is studied. The distribution of the vertical (normal) component of magnetic field strength is calculated along the line near the HTS stack (1.5 mm above the stack), which is shown as dotted lines in figure 5. The center of HTS stack is on the coordinate \( x=25 \text{ mm} \). Also, an analysis of the trapped field is performed for 1 HTS layer.

Calculation was carried out using the models for current and magnetization. HTS stack is modelled as a set of superconducting thin layers. Parameters of the models are presented in Table 1. Maximal critical current density from (3) and equivalent to it maximal critical magnetization from (1) and are determined from the values of the critical current of HTS tape and geometry of superconducting layer:

\[ J_{c,\text{max}} = I_c / (t \cdot h), \]

\[ M_{c,\text{max}} = I_c / (2 \cdot h), \]  

(4)

(5)

where \( I_c \) – the value of critical current; \( h \) – thickness of the superconducting layer; \( t \) - width of the tape. The values of the critical magnetic field strength, as well as model parameters \( \alpha \) and \( \beta \) are chosen according to the approximate dependencies \( I_c(B) \) provided by the manufacturer. The temperature during calculations is assumed to be constant (\( T=77 \text{ K} \)). Critical temperature \( T_c=93 \text{ K} \). All calculations are performed using the EasyMag3D software for the numerical analysis of 3D electromagnetic fields, which is based on the integral equations and had been developed at the NRU «MPEI».
Table 1. Parameters of the mathematical models.

| Model for currents | Model for magnetization | Simplified model |
|--------------------|--------------------------|------------------|
| $J_{C_{\text{max}}}$ | $27778$ A/mm² | $M_{C_{\text{max}}}$ | $166667$ kA/m |
| $H_{C}$ | $2300$ kA/m | $H_{C_{\text{CM}}}$ | $2300$ kA/m |
| $\alpha$ | $2$ | $\alpha$ | $2$ |
| $\beta$ | $1$ | $\beta$ | $1$ |

Figure 5. Calculation of the trapped magnetic field (dimensions on the scheme in mm):
1 – model for magnetization (1 layer);
2 – model for currents (1 layer);
3 – model for magnetization (10 layers);
4 – model for current (10 layers).

The difference in the distribution of the magnetic field strength is observed in the middle part of the tape, where the model for current has a maximum and the model for magnetization has a dip. This effect is quite explainable. In the first case, currents upon reaching critical values fill the entire superconducting layer. Half of the tape has current in one direction and the other half in the opposite direction. While magnetization is equivalent only to currents at the outer borders of the tape.

The possibility of using the model for magnetization in the calculation of forces is illustrated by the following test problem. The magnetic system is taken from the previous task, but to create an inhomogeneous magnetic field, one magnet is removed. The same HTS stack is cooled in the field of a permanent magnet (FC mode) on a distance of $3$ mm from the magnet. Then the magnet moves up $100$ mm and returns to its initial position. Figure 6 shows the calculating dependences of the force, acting on the stack, on the displacement of a permanent magnet. Results are obtained for three models: model for currents, model for magnetization, and simplified calculation when HTS stack is modelled as a bulk superconductor with equivalent properties.

For the third type, the parameters of the model for magnetization are shown in Table 1 in the last two columns. In this case, the maximum value of the critical magnetization is determined as

$$M_{C_{\text{max}}} = \frac{N \cdot J_{C}}{2 \cdot h_{1}},$$

where $N$ – number of superconducting layers; $h_{1} = 1.2$ mm – thickness of the HTS stack.

Figure 6. Dependencies of the force acting on the HTS stack on the displacement of a permanent magnet (dimensions on the scheme in mm):
1 – model for current;
2 – simplified model for magnetization (bulk);
3 – model for magnetization (HTS stack with 10 layers).
The difference in the results of the calculation of force for the considered test problem is associated with the possible inaccuracies in determining the properties of the materials and assumption of the piecewise homogeneous magnetization.

Used parameters of the model for magnetization, except the maximum critical magnetization, had been taken equal to the model for currents. To reduce the discrepancies, the parameters magnetization curve shown in figure 2(b) must be determined using additional experimental measurements.

The maximum values of the force are reached when the currents are distributed over the all cross-section of the HTS tape, not just only near the edges. In this case, homogeneous magnetization cannot describe the induced currents. This leads to an increase in the error when replacing the type of source describing the induced currents. Using the simplified model with equivalent superconducting bulk shows an increase in error due to a less accurate approximation, but reduces the calculation time.

3.2. Comparison with experiment

A comparison of experimental data and calculation results using the model for magnetization are performed for the HTS coil with 17 turns made of 12 mm 2G HTS tape (figure 7(a,b)). The ends of the coil are not electrically joined, thus only vortex currents can be induced as shown in Fig.1. Measurements of a trapped magnetic field in the HTS coil were performed on the laboratory setup, which is shown in figure 7(c). The coil is placed inside the vessel and cooled by liquid nitrogen (77 K) in the field of permanent magnets. After cooling the magnet system is removed far from the HTS coil (by 500 mm) and magnetic field near the coil is measured. The dimensions of magnetic system and position of the HTS coil and the entire system in the initial (cooling) state are shown in figure 8(a). The configuration of the magnetic system and directions of the magnetization vectors in permanent magnet sectors – in figure 8(b). Magnetization of all permanent magnets is 980 kA/m.

Due to the vortex structure of the induced currents in an open-circuit coil, their distribution is similar to the HTS stack discussed above and the model for magnetization can be used. In figure 8(c), the magnetic field distributions near the HTS coil obtained by calculation and experimental measurement are compared. Distribution of the normal component of the magnetic field strength (perpendicular to the surface of the tape) was measured along the diameter of the coil at a distance of 7 mm from its edge (dotted line in Fig.8(a)) and ±45 mm from the center of the coil. The parameters of HTS tape are the same as in previous tasks (the 2nd model in Table 1). Calculations are performed

![Figure 7. Laboratory equipment: (a) – drawing of the studied HTS coil (dimensions in mm); (b) – photo of the studied HTS coil; (c) – experimental setup: 1 – permanent magnet; 2 – measuring probe; 3 – vessel with the sample; 4 – coordinate mechanism; 5 – pipe for filling liquid nitrogen.](image-url)
using the model for magnetization of HTS stack, taking into account the properties of each turn of the coil individually. In this study, calculation results have a good approximation with experimental data.

![Diagram of HTS coil and magnetization vectors](image)

**Figure 8.** Experiment with HTS coil: (a) – the entire system in the initial position (dimensions in mm); (b) – magnetization vectors of the magnet sectors; (c) – distribution of the trapped magnetic field above the HTS coil: calculation – solid line, experiment – dashed line.

Comparison of the proposed model for magnetization with the known model for currents and experimental results confirms the reliability of the model for magnetization and method of determining the critical parameters, and possibility of applying it for calculations of HTS bearing with open-circuit superconducting coils. Discrepancies with experimental data are associated with measurement errors at low temperature, as well as assumptions of the model that were previously described during comparison with the model for currents.

### 4. Calculations of magnetic bearings

Calculation of magnetic bearings with HTS tapes was started from the construction investigated in work [6]. The design of the magnetic system of the bearing is shown in figure 9(a). Superconducting part consists of three pancake coils. Each coil has 39 turns of 12 mm 2G HTS tape. The coils are open-circuit and not connected to each other. Inside the HTS coils, there are two disk permanent magnets that are fixed by the same poles. Permanent magnets have magnetization of 1000 kA/m. The gap between the permanent magnets and HTS coils is 2.5 mm.

![Diagram of HTS bearing and force vs displacement](image)

**Figure 9.** HTS bearing with HTS coils: (a) – HTS bearing magnetic system design (dimensions in mm); (b) – dependence of axial force on the axial displacement of permanent magnets. Calculation with tapes – solid line; calculation with a solid array (bulk) – dashed line; experimental data from [6] – dotted line.

HTS coils are cooled in the magnetic field of permanent magnets at the initial position which is shown in figure 9(a). After cooling, permanent magnets are moved along the axis of the bearing by 40 mm and then back to the starting position. The temperature during the experiment is 77 K.
The arising forces during axial displacement were calculated using the model for magnetization of HTS layers and the simplified model for equivalent bulk. In the experimental study the same 12 mm HTS tape with critical current 500 A was used, thus the parameters of the model for magnetization were taken as in previous tasks (the 2nd model in Table I). The maximum critical magnetization for the simplified model \( M_{C,max} = 3305 \text{ kA/m} \) is defined from (6) with the following values: \( N=39, h_1=2.95 \text{ mm} \). Other parameters remain unchanged.

The results of modeling are shown in figure 9(b) and comparison with the experimental data presented in [6]. The discrepancy between the calculation results and the experiment is possibly due to the inaccuracy of the initial data, including the properties of using materials.

As noted in [6] the experimental curve shows highly irreversible behavior. This could be explained by the penetration of the magnetic field inside the tape and re-trapping of the field by HTS tape, which is caused by factors not taken into account in the calculation, for example, local changes in the temperature in the tape and, accordingly, its critical parameters. At lower temperatures, these curves have similar forms as calculated.

Figure 10 shows the results of calculations of the radial HTS bearing for the flywheel energy storage system considered in [11]. The bearing consists of four ring permanent magnets with alternating axial directions of magnetization. Between the magnets, there are steel magnetic flux concentrators. The HTS element has the form of a hollow cylinder, which is located inside the permanent magnets. The gap between magnets and HTS is 1.3 mm. HTS element is made of YBaCuO bulks with a critical current density of 230 A/mm², which was defined from the experiments. Magnetization of permanent magnets is 1000 kA/m.

The construction and characteristics of HTS bearing were previously studied and here obtained data are compared with the results of calculations of a bearing with an HTS tape. Bulk HTS cylinder is replaced by the three coils with 17 turns of 10 mm HTS tape with the same external diameter. The critical current of HTS tape is taken 500 A. Calculations are performed using the model for magnetization with previously presented parameters (Table I) and the simplified model with the maximum critical magnetization \( M_{C,max} = 2083 \text{ kA/m} \) defined from (6) with following values: \( N=17, h_1=2.04 \text{ mm} \).

\[ \text{Figure 10. Radial HTS bearing: (a) – design of HTS bearing (dimensions in mm); (b) – dependence of axial force on axial displacement of permanent magnets; (c) – dependence of radial force on radial displacement of permanent magnets. Calculation of individually tapes – solid line; calculation of simplified equivalent bulk – dashed line; previously obtained experimental data – dotted line.} \]

HTS elements are cooled in a magnetic field of permanent magnets (FC) at the initial position (\( T=77 \text{ K} \)), which is shown in figure 10(a). After cooling, permanent magnets are moved and force acting on HTS is calculated. Figure 10(b) shows the axial force during the axial motion of the permanent magnet system from the initial point up to 4 mm and backward. Figure 10(c) shows the radial force during the displacement of permanent magnets in the radial direction (changing of the gap) from the initial point up to 1 mm and backward. Results of calculation using both models for the radial force show good agreement. The discrepancy between the calculations is observed for the axial force primarily at large displacements when the currents are close to critical values. This is caused by the use of the assumption of piecewise-homogeneous regions of magnetization and less accurate mesh.

Comparison of the characteristics of the bearing with HTS tapes with previously obtained data for the bearing with HTS bulks allows us to evaluate the possibility of using HTS tapes for magnetic
bearings. In the operating area of displacements – ±1 mm for axial displacement and ±0.5 mm for radial displacement, similar force characteristics are achieved with significantly smaller dimensions of the HTS elements. At large displacements, the currents penetrate the superconductor and distributed over the all volume of the HTS, not just only near the surface. Due to the features of the current distribution in the coils, as well as a smaller volume superconducting material the maximum value of axial force is less than in the magnetic system with HTS bulks.

5. Conclusion

The proposed model for magnetization represents the current structures by the density of their magnetic moments, i.e. magnetization. This model can be used in the case of vortex currents structure, such as in open-circuit coils in HTS bearing. Replacing the induced currents with an equivalent distribution of magnetization allows to consider the non-stationary problem as the stationary one and simplify the calculation procedures.

Comparison of the model for current and the model for magnetization shows the differences in the distribution of the trapped magnetic field and forces, which can be explained by the inaccuracies in determining the properties of the materials and assumption of the homogeneous magnetization. To increase the accuracy of the developed model for magnetization the additional experimental measurements of magnetization curve are needed. In order to approximate the model properties for currents and for magnetization, inhomogeneous critical parameters of magnetization can be used. Also, it was shown that the calculation of magnetic bearings with HTS tapes can be performed using simplified models for equivalent HTS bulk with magnetization.

The construction of previously studied radial HTS bearing with bulk superconductors was analyzed in case of using HTS tapes. The results of comparison show that applying HTS tapes for magnetic suspensions allows to create more compact designs that are simpler to manufacture.

References

[1] Yu Z, Zhang G, Qiu Q, Hu L, Zhang D and Qiu M 2015 IEEE Trans. Appl. Supercond. 25, 3600605
[2] Werfel F N, Floegel-Delor U, Riedel T, Rothfeld R, Wippich D and Goebel B 2010 IEEE Trans. Appl. Supercond. 20 874-879
[3] Kurbatov P and Kurbatova E 2014 Proc. of IEEE SIELA’2014 6871866
[4] Subkhan M and Komori M 2011 IEEE Trans. Appl. Supercond. 21 1485-88
[5] Kurbatova E 2018 IEEE Trans. Appl. Supercond. 28 5207704
[6] Patel A, Hopkins S C, Baskys A, Kalitka V, Molodyk A and Glowacki B A 2015 Supercond. Sci. Technol. 28 115007
[7] Sass F, Sotelo G, Polasek A and Andrade R 2011 IEEE Trans. Appl. Supercond. 21 1511-14
[8] Han Z, Chen Q, Li L, Cao J, Xu F and Chan C C 2018 IEEE Trans. Appl. Supercond. 28, 8001208
[9] Sotelo G G, Carrera M, Lopez-Lopez J, and Granados X 2016 IEEE Trans. Appl. Supercond. 26, 6603510
[10] Kulaev Y V, Kurbatov P A, Kurbatova E P, Matveev V A, Maevskii V A, Nizhel’skii N A and Sysoev M A 2015 Russ. Electr. Engineer. 86 213-219
[11] Derbachev P, Kosterin A, Kurbatova E and Kurbatov P 2016 Proceed. IEEE Intern. Power Electr. and Motion Contr. Conf. 574-579