US 20160177937A1

(19) **United States**

(12) **Patent Application Publication**

Liu et al.

(10) **Pub. No.: US 2016/0177937 A1**

(43) **Pub. Date: Jun. 23, 2016**

(54) **METHOD FOR DETERMINING A PHYSICAL VARIABLE IN A POSITIVE DISPLACEMENT PUMP**

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(21) Appl. No.: **14/907,851**

(22) PCT Filed: **Aug. 21, 2014**

(86) PCT No.: **PCT/EP2014/067816**

§ 371 (c)(1),
(2) Date: **Jan. 27, 2016**

(30) **Foreign Application Priority Data**

Aug. 29, 2013 (DE) 10 2013 109 410.4

Publication Classification

(51) **Int. Cl.**

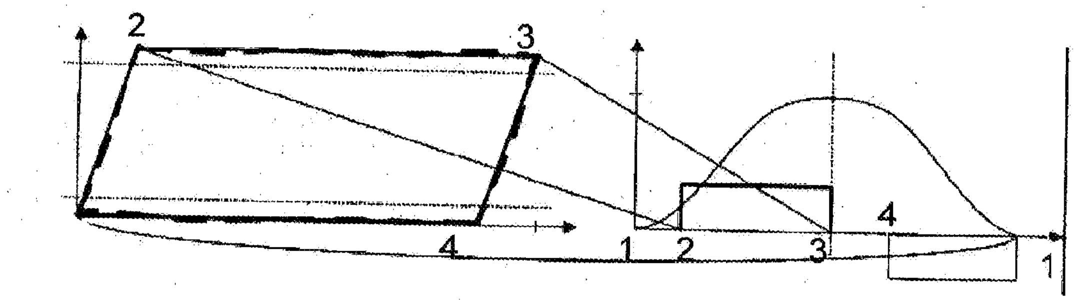
F04B 49/02	(2006.01)
F04B 13/00	(2006.01)
F04B 49/20	(2006.01)
F04B 53/10	(2006.01)
F04B 43/04	(2006.01)
F04B 49/06	(2006.01)

(52) **U.S. Cl.**

CPC ***F04B 49/022*** (2013.01); ***F04B 43/04*** (2013.01); ***F04B 49/06*** (2013.01); ***F04B 49/20*** (2013.01); ***F04B 53/10*** (2013.01); ***F04B 13/00*** (2013.01)

(57) **ABSTRACT**

The present invention relates to a method for determining at least one physical variable in a positive displacement pump, wherein the positive displacement pump has a movable displacer element which delimits the metering chamber which is connected via valves to a suction and pressure line, with the result that delivery fluid can alternately be sucked into the metering chamber via the suction line and can be pressed out of the metering chamber via the pressure line as a result of an oscillating movement of the displacer element, wherein a drive is provided for the oscillating movement of the displacer element.



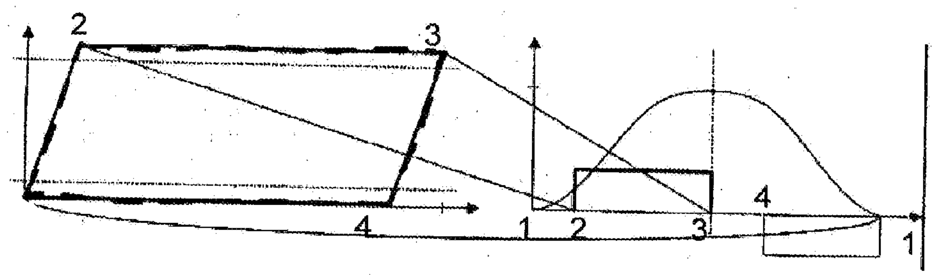


Figure 1

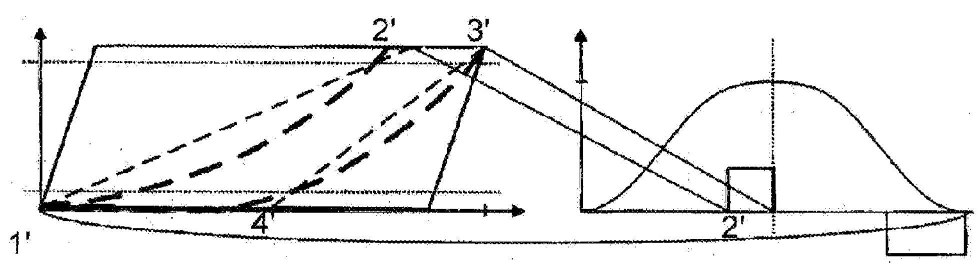


Figure 2

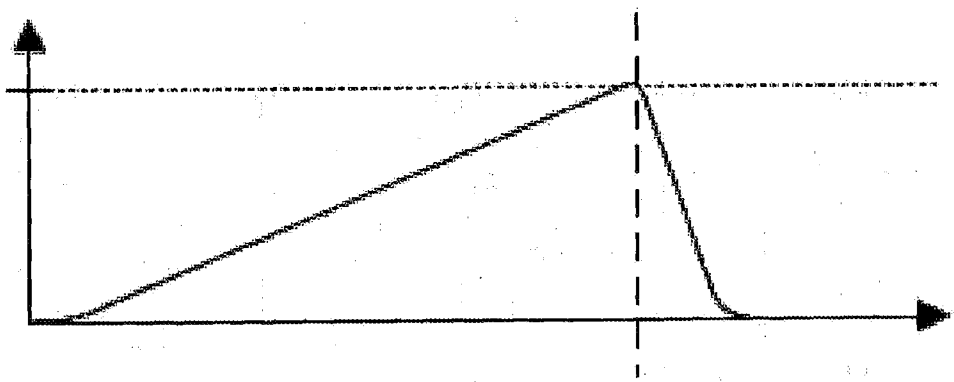


Figure 3

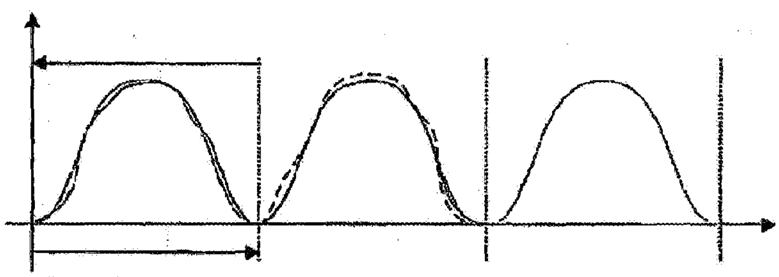


Figure 4

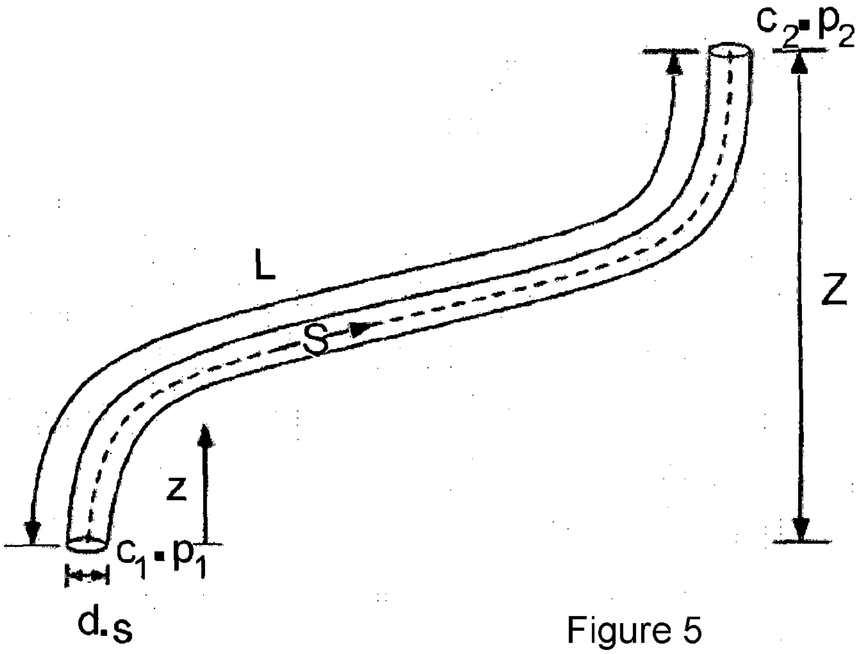


Figure 5

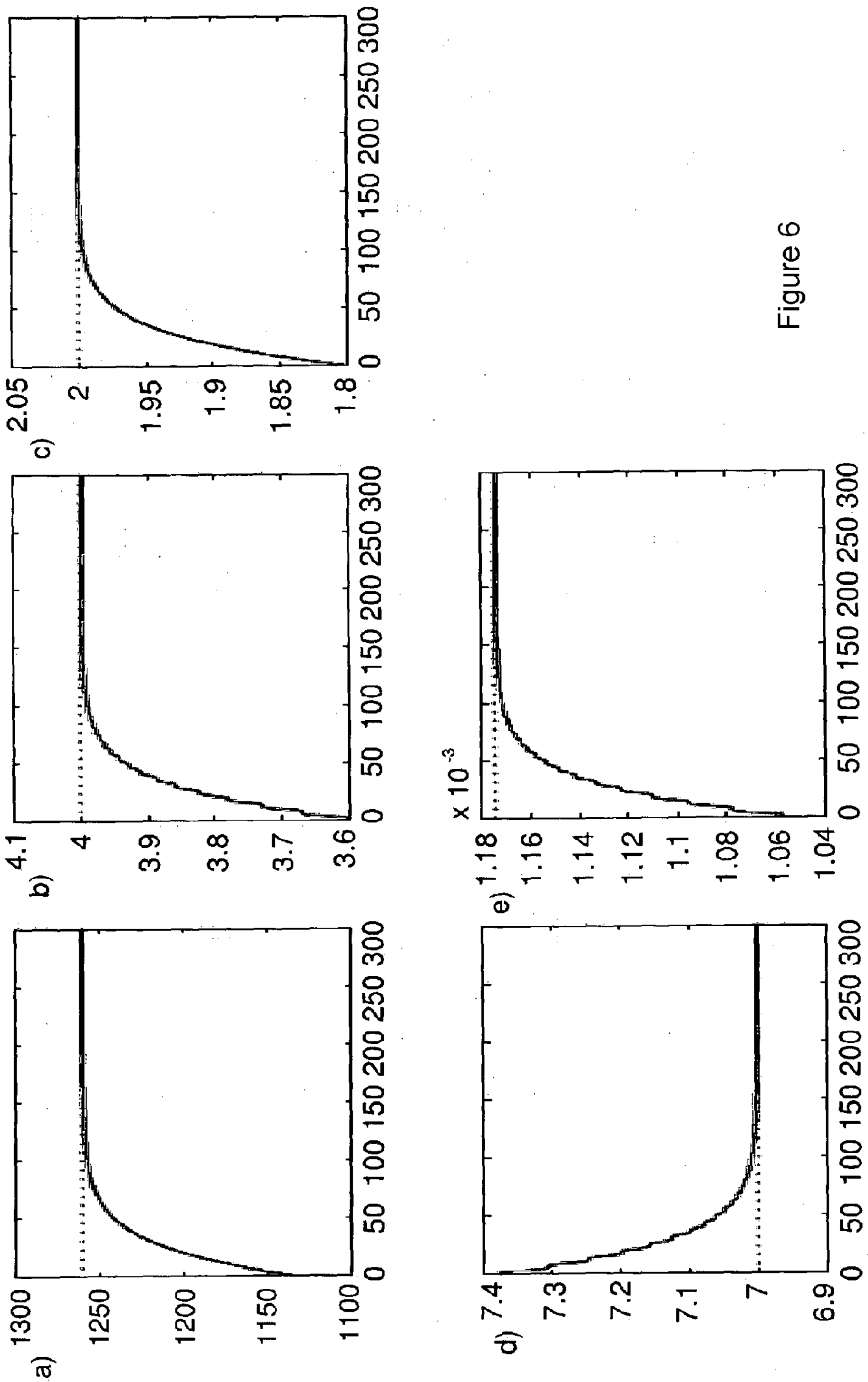


Figure 6

METHOD FOR DETERMINING A PHYSICAL VARIABLE IN A POSITIVE DISPLACEMENT PUMP

[0001] The present invention concerns a method for determining a physical variable in a positive displacement pump.

[0002] Positive displacement pumps generally have a moveable displacer element delimiting the metering chamber which in turn is connected by way of valves to a suction line and a pressure line. The result of this is that delivery fluid can alternately be sucked into the metering chamber by way of the suction line by an oscillating movement of the displacer element and can be urged out of the metering chamber by way of the pressure line. A drive for the oscillating movement of the displacer element is provided for that purpose.

[0003] There are for example electromagnetically driven diaphragm pumps in which the displacer element is a diaphragm which can be reciprocated between two extreme positions, wherein the volume of the metering chamber is at a minimum in the first extreme position while the volume of the metering chamber is at a maximum in the second extreme position. If therefore the diaphragm is moved from its first position into the second then the pressure in the metering chamber will fall so that delivery fluid is sucked into the metering chamber by way of the suction line. In the return movement, that is to say in the movement from the second into the first position, the connection to the suction line is closed, the pressure of the delivery fluid will rise by virtue of the decreasing volume in the metering chamber so that the valve to the pressure line is opened and the delivery fluid is delivered into the pressure line. Delivery fluid is alternately sucked into the metering chamber from the suction line and delivered from the metering chamber into the pressure line alternately by the oscillating movement of the diaphragm. The delivery fluid flow in the pressure line is also referred to as the metering profile. That metering profile is substantially determined by the movement profile of the displacer element.

[0004] In the case of electromagnetically driven diaphragm pumps the diaphragm is connected to a pressure portion which in most cases is supported in resiliently prestressed fashion at least partially within a solenoid. As long as the solenoid does not have a current flowing therethrough so that no magnetic flux is built up in its interior the resilient prestressing provides that the pressure portion and therewith the diaphragm remains in a predetermined position, for example the second position, that is to say the position in which the metering chamber is at the largest volume.

[0005] If now a current is impressed on the solenoid a magnetic flux is produced which moves the appropriately designed pressure portion within the solenoid from its second position into the first position whereby the delivery fluid in the metering chamber is delivered therefrom into the pressure line.

[0006] Therefore activation of the solenoid substantially abruptly involves a stroke movement of the pressure portion and therewith the metering diaphragm from the second position into the first position.

[0007] Typically such electromagnetically driven diaphragm pumps are used when the fluid volume to be metered is markedly greater than the volume of the metering chamber so that the metering speed is essentially determined by the frequency or the cycling of the flow of current through the solenoid. If for example the metering speed is to be doubled then the solenoid is briefly powered with a current twice as frequently in the same time, which in turn has the result that the movement cycle of the diaphragm takes place twice as frequently.

[0008] Such a magnetic metering pump is described for example in EP 1 757 809.

[0009] The use of such magnetic metering pumps however encounters its limits when only low metering speeds are required so that the abrupt metering action of an entire stroke movement is not wanted.

[0010] Above-mentioned EP 1 757 809 therefore already proposes providing a position sensor with which the position of the pressure portion or the diaphragm connected thereto can be determined. Closed-loop control of the movement can then be effected by a comparison between the actual position of the pressure portion and a predetermined target position of the pressure portion.

[0011] The closed-loop control of the movement of the pressure portion provides that magnetic metering pumps can also be used for delivering markedly smaller amounts of fluid as the stroke movement no longer takes place abruptly but in a regulated fashion.

[0012] Particularly when the metering amounts are very small for example valve opening and valve closing times of the metering pump play a substantial part as they determine the beginning and the end of the actual metering operation.

[0013] In addition gas bubbles in the hydraulic system and/or cavitation phenomena in the pump head of the metering unit can reduce the actual metering amount, which can markedly reduce the metering accuracy in particular when very small metering amounts are involved.

[0014] It is therefore possible in principle for example to measure the fluid pressure in the metering chamber with a pressure sensor and to use the measurement results to establish conclusions about processes in the metering head like for example gas bubbles in the hydraulic system, cavitation phenomena and/or an excess pressure in the metering head.

[0015] Such a pressure sensor however increases the cost of the metering pump, it is susceptible to faults and it has to be maintained.

[0016] Particularly when the metering pump is to be used in the foodstuffs industry the metering chamber has to be regularly very thoroughly cleaned.

[0017] In the cleaning operation product fluid residues are to be carefully removed from all recesses which occur for example at junctions. The presence of an additional sensor which is in contact with the pressure fluid therefore increases the cleaning complication and effort as the junction between sensor and metering chamber has to be additionally cleaned.

[0018] Therefore the object of the present invention is to provide a method of determining a physical variable, for example the fluid pressure, with which that variable can be determined without using an additional sensor.

[0019] According to the invention that object is attained in that for the displacer element a differential equation is established based on a physical model, at least the position of the displacer element is measured and the physical variable, for example the fluid pressure, is determined by means of the differential equation. For example the differential equation can be a movement equation. The term movement equation is used to denote a mathematical equation which describes the spatial and temporal movement of the displacer element under the action of external influences.

[0020] The present invention is firstly described hereinafter referring to the example of determining the fluid pressure.

The invention however is not limited to determining the fluid pressure. Further examples are described further hereinafter.

[0021] Measurement of the position of the displacer element can be effected for example in contact-free manner and is in any case generally effected in the described metering pumps so that the information about the currently prevailing position of the displacer element is available. The movement equation of the displacer element takes account of all forces acting on the displacer element. Besides the force applied to the displacer element by the drive this is also the counteracting force applied by the fluid pressure in the metering chamber to the diaphragm and thus to the displacer element.

[0022] Therefore, if the force applied to the displacer element by the drive is known, conclusions about the fluid pressure in the metering head can be drawn from the position of the displacer element or from the speed, which can be deduced therefrom, or acceleration, of the displacer element.

[0023] In a preferred embodiment the positive displacement pump is an electromagnetically driven metering pump, preferably an electromagnetically driven diaphragm pump.

[0024] In that case it is advantageous if besides the position of the displacer element the current through the electromagnetic drive is also measured and the differential equation is used both for the position of the displacer element and also for the current through the electromagnetic drive as measurement variables. In general no further measurement variables to be detected are necessary. The force on the displacer element by the drive can be determined by measurement of the position of the displacer element and measurement of the current through the electromagnetic drive and then the pressure in the metering head can be determined from the movement of the displacer element.

[0025] For example if the actual fluid pressure reaches or exceeds a predetermined maximum value, a warning signal can be output and the warning signal can be sent to an automatic shut-down arrangement which shuts down the metering pump in response to reception of the warning signal. If therefore for any reason a valve should not open or the pressure on the pressure line should rise greatly, that can be ascertained by the method according to the invention without using a pressure sensor and the pump can be shut down for the sake of safety. Basically the displacer element with the associated drive additionally performs the function of the pressure sensor.

[0026] In a further preferred embodiment of the method for a movement cycle of the displacer element a target fluid pressure curve, a target position curve of the displacer element and/or the target current pattern through the electromagnetic drive is provided. In that case the actual fluid pressure can be compared to the target fluid pressure, the actual position of the displacer element can be compared to the target position of the displacer element and/or the actual current through the electromagnetic drive can be compared to a target current through the electromagnetic drive and a warning signal can be output if the differences between the actual and target values satisfy a predetermined criterion.

[0027] That method step is based on the notion that given events like for example gas bubbles in the hydraulic system or cavitation in the pump head cause a recognizable change in the fluid pressure to be expected and therefore conclusions about said events can be drawn from the step of determining the fluid pressure.

[0028] The warning signal can activate for example an optical display or an acoustic display. Alternatively or in combination therewith however the warning signal can also be made available directly to a control unit which implements suitable measures in response to reception of the warning signal.

[0029] In the simplest case the difference between actual and target values is determined for one or more of the measured or given variables and a warning signal is output if one of the differences exceeds a predetermined value.

[0030] In order however not only to detect the possible fault events like for example gas bubbles in the metering chamber or the occurrence of cavitation but also to distinguish them from each other it is possible to define a dedicated criterion for each fault event.

[0031] In a preferred embodiment a weighted sum of the relative deviations from the target value can be determined and the criterion so selected that a warning signal is output if the weighted sum exceeds a predetermined value.

[0032] Different weighting coefficients can be associated with the different fault events. In the ideal case, upon the occurrence of a fault event, precisely one criterion is met so that the fault event can be diagnosed.

[0033] Therefore the step of determining the pressure in the metering head is possible by the described method without having recourse to a pressure sensor and conclusions about given conditions in the metering head can be drawn from the pressure determined in that way, and they can then in turn trigger the initiation of given measures.

[0034] Pressure variations can be very precisely determined with the method according to the invention.

[0035] In a further embodiment therefore the time gradient of a measured or given variable is ascertained and, if it exceeds a predetermined limit value, valve opening or valve closure is diagnosed.

[0036] In an alternative embodiment, the mass m of the displacer element, the spring constant k of the spring prestressing the displacer element, the damping d and/or the electrical resistance R_{Cu} of the electromagnetic drive are determined as the physical variable.

[0037] In a particularly preferred embodiment even all of said variables are determined. That can be effected for example by a minimization calculation. All the specified variables with the exception of the pressure in the metering chamber represent constants which can be determined by experiment and which generally do not change in pump operation. Nonetheless fatigue phenomena in respect of the different elements can occur, which change the value of the constants. For example the measured pressure-travel relationship can be compared to an expected pressure-travel relationship. The difference integrated over a cycle from both relationships can be minimized by a variation in the constant parameters. If in that case it is established for example that the spring constant has changed a defective spring can be diagnosed.

[0038] Such a minimization operation could also be carried out in the pressure-less condition, that is to say when there is no fluid in the metering chamber.

[0039] The method according to the invention can be further developed in the preferred embodiment in order to improve the closed-loop control of the pressure portion movement, more specifically without previous tabling of control parameters being necessary. The metering profile which can be achieved with the positive displacement pump can be improved thereby.

[0040] For that purpose a model-based closed-loop control, in particular a non-linear model-based control, is used for the drive of the displacer element.

[0041] In the case of a model-based control a model which is as complete as possible of the process dynamic is developed. By means of that model, in simplified terms, it is then possible to make a prediction as to where the system variables will move in the next moment.

[0042] A suitable adjusting parameter can then also be calculated from that model. A characteristic of such a model-based control is therefore ongoing calculation of the necessary adjusting parameter on the basis of measurement variables using the system parameters given by the model.

[0043] Basically the fundamental physical system is approximately mathematically described by the modeling. That mathematical description is then used to calculate the adjusting parameter on the basis of the measurement variables obtained. Unlike the known metering profile optimization methods therefore the drive is no longer viewed as a “black box”. Instead the known physical relationships are used for determining the adjusting parameter. The differential equation according to the invention of the displacer element can be used for that purpose.

[0044] In that respect, in a preferred embodiment, forces which are specific to the positive displacement pump and which act on the pressure portion are modeled in the differential equation. Thus for example the force exerted on the pressure portion by a spring, or the spring constant k thereof, and/or the magnetic force exerted on the pressure portion by the magnetic drive can be modeled. The force exerted on the pressure portion by the delivery fluid can then be treated as an interference variable.

[0045] A prediction for the immediately following system behaviour can then be made by such a state space model, if the measurement variables are detected.

[0046] If the immediately following behaviour prognosticated in that way deviates from the desired predetermined behaviour a correcting influence is applied to the system.

[0047] In order to calculate how a suitable influencing looks the influence of the available adjusting parameters on the closed-loop control variable can be simulated in the same model. The instantaneously best control strategy can then be adaptively selected by means of known optimization methods. As an alternative thereto it is also possible on the basis of the model to determine a control strategy as a one-off and then to apply same in dependence on the detected measurement variables.

[0048] In a preferred embodiment therefore a non-linear state space model is selected, wherein the non-linear closed-loop control is effected either by way of control-Lyapunov functions, by way of flatness-based closed-loop control methods with flatness-based precontrol, by way of integrator backstepping methods, by way of sliding mode methods or by way of predictive closed-loop control. In that case non-linear closed-loop control by way of control-Lyapunov functions is preferred.

[0049] All five methods are known from mathematics and are therefore not discussed in greater detail here.

[0050] Control-Lyapunov functions are for example a generalized description of Lyapunov functions. Suitably selected control-Lyapunov functions lead to a stable behaviour in the context of the model.

[0051] In other words, a correction function is calculated, which in the underlying model leads to a stable solution to the model.

[0052] In general there are a multiplicity of control options which have the result that the difference between actual profile and target profile becomes smaller in the underlying model.

[0053] In a preferred embodiment the model which forms the basis for the model-based closed-loop control is used for formulating an optimization problem in which as a secondary condition in respect of optimization, the electrical voltage at the electric motor and thus the energy supplied to the metering pump become as small as possible, but at the same time an approximation of the actual profile to the target profile which is as fast as possible and which has little overshoot is achieved. In addition it may be advantageous if the measured signals are subjected to low-pass filtering prior to processing in the fundamental model in order to reduce the influence of noise.

[0054] In a further particularly preferred embodiment it is provided that during a suction-pressure cycle the difference between the detected actual position profile of the displacer element and a desired target position profile of the displacer element is detected and a target position profile corresponding to the desired target position profile reduced by the difference is used for the next suction-pressure cycle.

[0055] Basically a self-learning system is implemented here. Admittedly the model-based closed-loop control according to the invention has already led to a marked improvement in the control characteristic, nonetheless there can be deviations between the target profile and the actual profile. That is not to be avoided in particular in the energy-minimizing selection of the control intervention. In order further to reduce that deviation at least for following cycles the deviation during a cycle is detected and the detected deviation is at least in part subtracted from the desired target position profile in the next cycle.

[0056] In other words, a “false” target value profile is intentionally predetermined for a following pressure-suction cycle, wherein the “false” target value profile is calculated from the experience acquired in the preceding cycle. If more specifically the following suction-pressure cycle entails exactly the same deviation between actual and target profile as in the preceding cycle, the use of the “false” target value profile has the result that the actually desired target value profile is achieved as a consequence.

[0057] Admittedly it is basically possible and by virtue of the periodic behaviour of the system in some applications also sufficient for the described self-learning step to be performed only once, that is to say for the difference to be measured in the first cycle and for the target value profile to be appropriately corrected as from the second and in all further cycles. It is particularly preferred however if the difference between actual and target profile is determined at regular intervals, best in each cycle, and is correspondingly taken into account in the following cycle.

[0058] It will be appreciated that it is also possible to use only a fraction of the detected difference as profile correction for the following cycle or cycles. That can be advantageous in particular in situations in which the detected difference is very great in order not to produce instability of the system due to the sudden change in target value.

[0059] In addition it is possible to determine the magnitude of the fraction of the detected difference, which is used as profile correction, on the basis of the currently prevailing difference between the target and the actual profiles.

[0060] It is also possible for the difference between the actual and the target profiles to be measured over a plurality of cycles, for example 2, and for a mean difference to be calculated therefrom, which is then at least in part subtracted from the target profile of the following cycles.

[0061] In a further alternative embodiment any function dependent on the detected difference can be used for correction of the next target position profile.

[0062] In a further particularly preferred embodiment it is therefore provided that a physical model with hydraulic parameters is also set up for the hydraulic system and at least one hydraulic parameter is calculated by means of an optimization calculation.

[0063] The term hydraulic parameters is used to mean any parameter of the hydraulic system—apart from the position of the displacer element—that influences the flow of the delivery fluid through the metering chamber.

[0064] Hydraulic parameters are therefore for example the density of the delivery fluid in the metering chamber and the viscosity of the fluid in that chamber. Further hydraulic parameters are for example hose or pipe lengths and diameters of hoses and pipes which are at least temporarily connected to the metering chamber.

[0065] That measure makes it possible to determine hydraulic parameters without having to provide an additional sensor.

[0066] An inherent property of the positive displacement pump is that the hydraulic system markedly changes whenever one of the valves, by way of which the metering chamber is connected to the suction and pressure lines, is opened or closed.

[0067] The system is simplest to model for the situation where the valve to the suction line is opened and the valve to the pressure line is closed. More specifically a flexible hose is frequently fitted to the valve to the suction line, and that hose ends in a supply container which is under ambient pressure.

[0068] That state occurs during the so-called suction stroke movement, that is to say while the displacer element is moving from the second position into the first position. That hydraulic system could be described for example by means of the non-linear Navier-Stokes equation, having regard to laminar and turbulent flows. Besides density and viscosity of the delivery fluid the diameter of the hose connecting the suction valve to the supply container, the length of the hose and the difference in height that the fluid in the hose has to overcome are then also to be considered as hydraulic parameters.

[0069] Depending on the respective system used further meaningful assumptions can be made. By means of an optimization calculation which can be effected for example by way of the known gradient method or Levenberg-Marquardt algorithms it is possible to determine the hydraulic parameters which are contained in the physical model and which best describe the pressure variation in the metering head and the movement or the speed and acceleration derived therefrom of the pressure portion.

[0070] In principle the determining method according to the invention could be effected solely by repeated analysis of the suction stroke performance.

[0071] As an alternative thereto however it is also possible to consider the physical model of the hydraulic system for the situation where the valve to the suction line is closed and the valve to the pressure line is open. As however the pump manufacturer initially does not generally know in what environment the metering pump is used and therefore also does not know the pipe system connected to the pressure valve connecting the pressure line to the metering chamber, only a generalized assumption can be made here. Therefore without knowledge of the pipe system connected to the pressure valve the physical model set up cannot be set up with the accuracy, as is generally possible for the hydraulic system during the suction stroke.

[0072] In a particularly preferred embodiment physical models for both described hydraulic systems are used and then the valve opening times are measured or determined and the respectively correct physical model is selected in dependence on the result of determining the valve opening time. Basically then the method according to the invention is carried out separately for the suction stroke and the pressure stroke. In both cases values which in practice are not exactly the same are obtained for the hydraulic parameters like for example the density and viscosity of the delivery fluid. In principle it would therefore be possible to average the different values, in which case here it is under some circumstances necessary to take account of the fact that, by virtue of the better description of the actual situation by the physical model during the suction stroke, the value obtained during the suction stroke is weighted more greatly in the averaging operation, than the value ascertained during the pressure stroke.

[0073] After the hydraulic parameters have been determined in the manner according to the invention the physical model set up can be used with the hydraulic parameters determined in that way in order in turn to determine the pressure in the metering chamber. That knowledge can be used in turn to improve the movement regulation of the pressure portion insofar as the force exerted on the pressure portion by the fluid is modeled by the hydraulic parameters determined in that way.

[0074] Further advantages, features and possible uses will be apparent from the description hereinafter of a preferred embodiment and the accompanying Figures in which:

[0075] FIG. **1** shows a diagrammatic view of a pressure-travel graph and a travel-time graph for the normal condition,

[0076] FIG. **2** shows a diagrammatic view of a pressure-travel graph and a travel-time graph for a condition with gas bubbles in the metering chamber,

[0077] FIG. **3** shows a diagrammatic view of an ideal movement profile,

[0078] FIG. **4** shows a diagrammatic view of the self-learning function,

[0079] FIG. **5** shows a diagrammatic view of the suction line connected to the positive displacement pump, and

[0080] FIGS. **6***a*-**6***e* show examples of hydraulic parameters and their time-dependent development.

[0081] The method according to the invention has been developed in connection with a magnetic metering pump. In a preferred embodiment such a metering pump has a moveable pressure portion with a thrust rod fixedly connected thereto. The pressure portion is supported axially moveably along the longitudinal axis in a magnet casing fixedly anchored in the pump housing so that the pressure portion with thrust rod is pulled into a bore in the magnet casing upon electrical actuation of the magnetic coil in the magnet casing, against the force of a compression spring, and the pressure portion reverts to the initial position due to the compression spring after deactivation of the solenoid. The consequence of this is that the pressure portion and a diaphragm actuated thereby, upon continued activation and deactivation of the magnetic coil, performs an oscillating movement which in the metering head arranged in the longitudinal axis, in conjunction with an outlet and inlet valve, leads to a pump stroke (pressure stroke) and an intake stroke (suction stroke). Activation of the magnetic coil is effected by applying a voltage to the coil. The movement of the pressure portion can thus be determined by the time pattern of the voltage at the coil.

[0082] It will be appreciated that the pressure stroke and the suction stroke do not necessarily have to last for the same period of time. As no metering is effected during the suction stroke but the metering chamber is only re-filled with delivery fluid, it is in contrast advantageous for the suction stroke in any case to be performed as quickly as possible, in which respect however care is to be taken to ensure that no cavitation occurs in the pressure chamber.

[0083] According to the invention therefore a (non-linear) model is developed, which describes the condition of the magnetic system.

[0084] The following model applies to a preferred embodiment:

$$\dot{x} = \begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{\Phi} \end{bmatrix} = \begin{bmatrix} \dot{x} \\ \frac{1}{m}(-d\dot{x} - kx - F_{vor} + F_p + K_L(\delta)\Phi^2) \\ \frac{1}{N_1}\left(-R_{cu}\frac{R_{m_{ges}}(\delta, \Phi)}{N_1}\Phi + u\right) \end{bmatrix}$$

wherein

[0085] m: mass of the pressure portion

[0086] Φ: magnetic flux

[0087] $K_L(\delta)\Phi^2$: magnetic force

[0088] N_1: number of turns

[0089] u: voltage

[0090] d: damping

[0091] k: spring constant

[0092] F_{vor}: force on pressure portion due to spring prestressing

[0093] F_p: force on pressure portion due to fluid pressure in the delivery chamber

[0094] $R_{m_{ges}}(\delta, \Phi)$: magnetic reluctance

[0095] R_{Cu}: ohmic resistance of the coil

[0096] x: position of the pressure portion

[0097] δ: gap size between armature and magnet

[0098] That is a non-linear differential equation system. It makes it possible to provide a prediction about the immediately following behaviour of the system, starting from a starting point.

[0099] By virtue of measuring the position of the pressure portion and the current through the magnetic drive F_p, that is to say the force on the pressure portion due to the fluid pressure in the delivery chamber, is the sole unknown variable. Therefore, using that model, it is possible to determine the force acting on the pressure portion due to the fluid pressure in the delivery chamber. As the area of the pressure portion subjected to the fluid pressure is known the fluid pressure can be calculated from the force.

[0100] The described drafting of a non-linear system description for the electromagnetic metering pump system makes it possible to use model-based diagnosis methods. For that purpose the state parameters of the system models are evaluated and the pressure in the pump head of the electromagnetic metering pump is determined. The necessary current and position sensors are in that case already installed in the pump system for control purposes so that the information is already available without the structure of the metering pump having to be supplemented. The diagnosis algorithms can then be performed on the basis of the time variation in the state parameters and the pressure in the metering head of the pump.

[0101] Thus for example the model-based diagnosis of process-side overpressure and the automated pump shut-down can be implemented.

[0102] Recognition of the valve opening and valve closing times can be effected for example by way of determining and evaluating time gradients of linked state parameters of the system model. A situation involving exceeding or falling below the state gradients can be detected by means of predetermined limits, which leads to a identification of the valve opening and valve closing times.

[0103] Alternatively thereto it is also possible to determine the pressure in dependence on the position of the pressure portion and to deduce the valve opening and valve closing times from an evaluation operation. A corresponding pressure-travel graph is shown at the left in FIG. **1**. The associated travel-time graph is shown at the right in FIG. **1**. The travel-time graph shows the time-dependent movement of the pressure portion. It will be seen that the pressure portion firstly moves forwardly from a starting position **1** (x=0 mm) and reduces the volume of the metering chamber (pressure phase). At time **3** the pressure portion passes through a maximum and then moves back into the starting position again (suction phase).

[0104] The associated pressure-travel graph is shown at the left in FIG. **1**. It is traveled in the clockwise direction, beginning at the coordinate origin at which the pressure portion is in position **1**. During the pressure phase the pressure in the metering chamber will initially rise steeply until the pressure is in a position of opening the valve to the pressure line. As soon as the pressure valve is opened the pressure in the metering chamber remains substantially constant. The opening point is identified by reference **2**. From that moment in time which is also shown at the right in FIG. **1** a metering action takes place. With each further movement of the pressure portion metering fluid is pumped into the pressure line. As soon as the pressure portion has reached the maximum position (time **3**) the movement of the pressure portion reverses, the pressure valve immediately closes and the pressure in the metering chamber falls again. As soon as a minimum pressure is reached (time **4**) the suction valve opens, connecting the metering chamber to the suction line, and metering fluid is sucked into the metering chamber until the starting position is regained.

[0105] The valve closing times can be determined from the travel-time graph as they are on the travel maxima of the pressure portion. The times **2** and **4**, that is to say the valve opening times, are not so easy to determine, especially as in practice the pressure-travel graph has rounded-off "corners". Therefore for example, starting from position **1** in the pressure-travel graph, upon reaching 90% of the pressure maximum (known from position **3**) the travel can be read off and the gradient of the pressure-travel graph between points **1** and **2** can be determined. The 90% curve is shown in dotted line. The resulting straight line intersects the curve $p=p_{max}$ at the valve opening time. The time **4** can also be determined in the same way. That determining operation can be effected in each cycle and the result used for a later cycle. In that way changes in the opening times are also detected.

[0106] Gas bubbles in the hydraulic system, cavitation in the pump head of the metering unit and/or valve opening and valve closing times of the metering units can be diagnosed by comparison of the target and actual trajectories of the individual state parameters. Particularly when a predetermined fault limit is exceeded between the target and actual trajectories that can trigger a warning signal and corresponding measures.

[0107] An example is shown in FIG. **2**. Here too the pressure-travel graph is shown at the left and the travel-time graph at the right. The right-hand Figure is identical to the corresponding graph in FIG. **1**. If there are gas bubbles which are compressible in the hydraulic system that can have the result that the pressure valve opens only at the time **2'** and the suction valve opens only at the time **4'**. A marked shift in the valve opening times can therefore be used to diagnose the state "air in the metering chamber". In the case of cavitation only the valve opening time **4'** and not the valve opening time **2** is shifted so that such a behaviour can be used to diagnose the state "cavitation".

[0108] The model-based method presented, by virtue of analysis of the individual linked system state parameters, permits a substantially more extensive and higher-grade diagnosis than was previously implemented.

[0109] In addition that can be achieved with low sensor system costs and a high level of reliability and certainty. The higher quality of diagnosis means that the area of use of electromagnetic metering pump systems can be enhanced under some circumstances as now the metering accuracy can be extremely improved.

[0110] In addition it is possible by means of the model to identify future or actually already existing deviations between the target curve and the actual curve. The model can also be used to calculate the probable influence of a control intervention.

[0111] In real time therefore measurement of the current strength and the position of the pressure portion determines how the system will probably develop. It is also possible to calculate the control intervention, that is to say the change in voltage at the magnetic coil, by which the system can be moved in the desired direction again.

[0112] To achieve a movement of the pressure portion, as shown in idealized form in FIG. **3**, the movement of the pressure portion has to be subjected to closed-loop control.

[0113] It will be appreciated that there are a multiplicity of possible ways of intervening in the system for closed-loop control. It is therefore possible at any moment in time to seek stable solutions for the dynamic system. That computing step is repeated continuously, that is to say as frequently as the available computing power allows, to achieve optimum closed-loop control.

[0114] With the model proposed here it is generally not necessary to determine new stable solutions of the dynamic system at every moment in time. In general it is sufficient for the suitable correction function to be determined once in dependence on the measurement variables, that is to say in dependence on the position of the pressure portion and the voltage at the magnet drive, and to use that correction function thereafter for the closed-loop control.

[0115] In spite of that closed-loop control there will inevitably be deviations between target and actual values as the selected model always represents an idealization. In addition the detected measurement variables are always error-afflicted (noise).

[0116] To further reduce the difference between actual and target profiles that difference is measured during a pressure-suction cycle and the sum of the measured difference and the desired target profile is used as the target profile for the following cycle. In other words, use is made of the fact that the pressure-stroke cycle is repeated. Thus in the following cycle there is predetermined a target value profile which deviates in relation to the target value profile that is actually wanted.

[0117] That self-regulating principle is diagrammatically shown in FIG. **4** for clarification purposes. This shows the position of the pressure portion on the Y-axis and time on the X-axis.

[0118] In the first cycle, a target profile used for the closed-loop control is illustrated in a broken line. That target profile corresponds to the desired target profile which is reproduced for comparison in the third cycle as the reference profile. In spite of the model-based closed-loop control according to the invention the actual profile will deviate from the target profile. In the first cycle in FIG. **4** therefore by way of example an actual profile is shown in solid line. In that case the deviations between the actual and target profiles are shown more pronounced for clarity than they occur in practice.

[0119] In the second cycle the difference between the actual profile of the first cycle and the reference profile is then subtracted from the target profile used for the first cycle and the difference is used as the target profile for closed-loop control during the second cycle. The target profile obtained in that way is shown in broken line in the second cycle.

[0120] In the ideal case in the second cycle the actual profile deviates to the same extent from the target profile used, as was observed in the first cycle. As a result there is an actual profile (shown in solid line in the second cycle), that corresponds to the reference profile.

[0121] By virtue of the design of a physical model, in particular a non-linear system description of the hydraulic process in the metering chamber or in the line connected to the metering chamber of an electromagnetic metering pump system, it is possible to use model-based identification methods in real time. For that purpose the hydraulic parameters, that is to say the state parameters of the hydraulic models, are evaluated and the system dynamic as well as the parameters of the hydraulic process are determined.

[0122] The position of the displacer element or the speed and acceleration which can be deduced therefrom of the displacer element and the pressure in the metering chamber which can be determined by way of the force exerted on the delivery fluid by the diaphragm serve as measurement variables or external variables to be determined.

[0123] As generally in the specified positive displacement pumps the suction line comprises a hose connecting the suction valve to a supply container the hydraulic system can be described in simplified form for the suction stroke, that is to say while the pressure valve is closed and the suction valve is opened, as is shown in FIG. **5**. The suction line comprises a hose of a diameter D_S and a hose length L. The hose bridges over a height difference Z.

[0124] The non-linear Navier-Stokes equations can be simplified if it is assumed that the suction line is of a constant diameter and is not stretchable and that an incompressible fluid is used.

[0125] By means of known optimization methods like for example the gradient method or the Levenberg-Marquardt algorithms, the hydraulic parameters are now determined, which on the basis of the model can best describe the measured or determined position of the pressure portion and the measured or determined pressure in the metering chamber.

[0126] FIGS. **6***a* through **6***e*, using the example of glycerin as the delivery fluid, here each show a hydraulic parameter (dotted line) and the values from the method according to the invention (solid line) in relation to time.

[0127] Thus for example FIG. **6***a* shows the density of the delivery fluid. That is about 1260 kg/m^3 (dotted line). It will be seen that the method according to the invention is in a position to determine the density within about 100 seconds. Admittedly, at the time t=0 seconds the given value is still markedly below the actual value. By virtue of ongoing optimization however the value determined by the method according to the invention for density very rapidly approaches the true value (solid line).

[0128] The same applies to the hose length L (see FIG. **6***b*), the height difference Z (see FIG. **6***c*), the hose diameter (see FIG. **6***d*) and viscosity (see FIG. **6***e*).

[0129] The parameters determined by the method according to the invention can then in turn be used together with the physical model produced to determine the force exerted on the pressure portion by the hydraulic system.

[0130] That information can be used for the closed-loop control according to the invention. Thus the hydraulic model developed can physically reproduce the influence of the hydraulic system and take account of same in the form of a disturbance variable intrusion.

[0131] That yet once again markedly improves the pump operation of electromagnetic metering pump systems.

1.-**16**. (canceled)

17. A method of determining at least one physical variable in a positive displacement pump,

wherein the positive displacement pump has a moveable displacer element delimiting the metering chamber which is connected by way of valves to a suction and a pressure line so that delivery fluid can alternately be sucked into the metering chamber by way of the suction line and urged out of the metering chamber by way of the pressure line by an oscillating movement of the displacer element,

wherein there is provided a drive for the oscillating movement of the displacer element,

wherein for the displacer element a differential equation is established based on a physical model, at least the position of the displacer element is measured and the physical variable is determined by means of the differential equation,

wherein the fluid pressure p of a delivery fluid in a metering chamber of a positive displacement pump is determined as the physical variable,

characterized in that if the actual fluid pressure reaches or exceeds a predetermined maximum value a warning signal is output and the warning signal is sent to an automatic shut-down arrangement which shuts down the metering pump in response to reception of the warning signal.

18. A method of determining at least one physical variable in a positive displacement pump,

wherein the positive displacement pump has a moveable displacer element delimiting the metering chamber which is connected by way of valves to a suction and a pressure line so that delivery fluid can alternately be sucked into the metering chamber by way of the suction line and urged out of the metering chamber by way of the pressure line by an oscillating movement of the displacer element,

wherein there is provided a drive for the oscillating movement of the displacer element,

wherein for the displacer element a differential equation is established based on a physical model, at least the position of the displacer element is measured and the physical variable is determined by means of the differential equation,

wherein the fluid pressure p of a delivery fluid in a metering chamber of a positive displacement pump is determined as the physical variable,

characterized in that for a movement cycle of the displacer element a target fluid pressure curve, a target position curve of the displacer element and/or the target current pattern through the electromagnetic drive is provided and the actual fluid pressure is compared to the target fluid pressure,

the actual position of the displacer element is compared to the target position of the displacer element and/or the actual current through the electromagnetic drive is compared to a target current through the electromagnetic drive and a warning signal is output if the differences between the actual and target values satisfy a predetermined criterion.

19. A method of determining at least one physical variable in a positive displacement pump,

wherein the positive displacement pump has a moveable displacer element delimiting the metering chamber which is connected by way of valves to a suction and a pressure line so that delivery fluid can alternately be sucked into the metering chamber by way of the suction line and urged out of the metering chamber by way of the pressure line by an oscillating movement of the displacer element,

wherein there is provided a drive for the oscillating movement of the displacer element,

wherein for the displacer element a differential equation is established based on a physical model, at least the position of the displacer element is measured and the physical variable is determined by means of the differential equation,

characterized in that the mass m of the displacer element, the spring constant k of the spring prestressing the displacer element, the damping d and/or the electrical resistance R_{Cu} of the electromagnetic drive is determined as the physical variable.

20. A method as set forth in claim **17**, characterized in that the positive displacement pump is an electromagnetically driven metering pump.

21. A method as set forth in claim **20** characterized in that besides the position of the displacer element the current through the electromagnetic drive is measured and the differential equation uses both the position of the displacer element and also the current through the electromagnetic drive as measurement variables, wherein the differential equation does not have any further measurement variables to be detected.

22. A method as set forth in claim **18** characterized in that a weighted sum of the relative deviations from the target value is determined and the criterion is so selected

23. A method as set forth in claim **18** characterized in that a plurality of criteria are predetermined, a fault event is associated with each criterion and, if a criterion is fulfilled, the associated fault event is diagnosed.

24. A method as set forth in claim **17** characterized in that a model-based closed-loop control is used for the drive.

25. A method as set forth in claim **24** characterized in that a non-linear state space model is selected as the model, wherein the non-linear closed-loop control is effected either by way of control-Lyapunov functions, by way of flatness-based closed-loop control methods with flatness-based pre-control, by way of integrator backstepping methods, by way of sliding mode methods or by way of predictive closed-loop control, wherein non-linear closed-loop control by way of control-Lyapunov functions is preferred.

26. A method as set forth in claim **24** characterized in that the difference between the detected actual position profile of the displacer element and a predetermined target position profile of the displacer element is detected during a suction-pressure cycle and the difference of at least a part of the detected difference and the predetermined target position profile is used as the target value profile for the next suction-pressure cycle.

27. A method as set forth in claim **17** characterized in that hydraulic parameters in the positive displacement pump are determined, for the hydraulic system a physical model is established with hydraulic parameters, the force exerted by the displacer element on the fluid in the metering chamber or the pressure in the metering chamber as well as the position of the displacer element is determined and at least one hydraulic parameter is calculated by means of an optimization calculation.

28. A method as set forth in claim **27** characterized in that the density of the fluid in the metering chamber and/or the viscosity of the fluid in the metering chamber is determined as the hydraulic parameter.

29. A method as set forth in claim **27** characterized in that the physical model is set up for the situation where the valve to the suction line is opened and the valve to the pressure line is closed and/or for the situation where the valve to the suction line is closed and the valve to the pressure line is opened, wherein if the physical model is set up both for the situation where the valve to the suction line is opened and the valve to the pressure line is closed and also for the situation where the valve to the suction line is closed and the valve to the pressure line is opened, the valve opening times are determined, and the physical model is selected in dependence on the result of determining the valve opening times.

30. A method as set forth in claim **28** characterized in that after determination of the hydraulic parameter same and the physical model is used for determining the force exerted by the delivery fluid on the displacer element and the force determined in that way is used in a closed-loop control of the movement of the displacer element.

31. A method as set forth in claim **18**, characterized in that the positive displacement pump is an electromagnetically driven metering pump.

32. A method as set forth in claim **19**, characterized in that the positive displacement pump is an electromagnetically driven metering pump.

33. A method as set forth in claim **18** characterized in that a model-based closed-loop control is used for the drive.

34. A method as set forth in claim **19** characterized in that a model-based closed-loop control is used for the drive.

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