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MECHATRONIC DRIVES

Аннотация

Цель данной статьи - показать читателям путь развития мехатронных приводов, от начала их развития, и до того, какими они являются сейчас. В статье так же описываются такие немаловажные компоненты как энкодеры, бесколлекторные двигатели постоянного тока, шаговые двигатели, ШИМ усилители и цифровые контроллеры. Так же в статье описано немало технических подробностей выше перечисленных компонентов, принципы их работы и то, для чего они используются.

Ключевые слова: энкодер, бесколлекторный двигатель постоянного тока, шаговый двигатель, ШИМ усилитель, цифровой контроллер.

Abstract

The purpose of this article is to show the readers the path of development of mechatronic drives, from the beginning of their development and to what they are now. The article also describes such important components as encoders, DC brushless motors, stepper motors, PWM amplifiers and digital controllers. The article also describes a lot of technical details of the above components, the principles of their operation and what they are used for.

Keywords: encoder, DC brushless motor, stepper motor, PWM amplifiers, digital controller.

MECHATRONIC DRIVES

Drives Evolution

Let’s observe the drive’s evolution. Drives evolution advances from a comparative low level of accuracy, reliability and service life to a high level of such features for modern drives. This evolution began from elementary drives. Such drive contains, for example, a gear, a DC motor, a linear amplifier, an analog controller and some simple analog transducers such as a potentiometer or a resolver. Main disadvantages of this drives are concluded in the following:

- Components of an elementary drive have a lot of contacts. For example, the commutator and brushes in a DC motor, the contact arm in a potentiometer, rings and brushes in a resolver, etc.
- Linear electronic amplifiers have very strong limit of the output power magnitude and small efficiency.
- Analog controllers with the operational amplifiers don't provide any effective dynamic correction for the stable action of the drive.

The next step in the drives evolution was to eliminate main disadvantages of an elementary drive by the broad employment of electronics. Such drive is called a mechatronic drive. It contains, for example, a mechanical gear, a brushless DC motor or a stepping one, a pulse-width modulated (PWM) amplifier, a digital controller and a digital transducer (encoder). A mechatronic drive has no any commutators, rings and brushes. Frequently it is called a brushless drive.

However, a brushless drive has some disadvantages too. The main point of these disadvantages is a mechanical gear between a motor and a plant. A mechanical gear has next drawbacks: a backlash, a kinematical error, resonance frequencies (mechanical resonances), etc. All these gear features strongly restrict an accuracy and a speed of response of every drive.

Hence, the next step was a gearless or a direct drive. The ”direct” means the direct connection of a motor and a plant without any gear. Furthermore a direct drive includes some last years achievements in electronics. It contains, for example, a permanent magnet synchronous motor (PMSM), a PWM amplifier with mainly integral circuitry (IC), 16-bit microcontroller and an absolute encoder as a transducer.

This drive evolution is accompanied by the evolution of all electromechanical components (motors and transducers).

Now the first generation includes all motors without any electronics. Here are all classic DC and AC motors such as DC motors (DCM), electromagnet clutches (EC), induction (IM) and synchronous (SM) motors. These motors contain only the stator and the rotor, cores from steel laminations and windings, steel and copper. Such machines are called electromechanical converters (EMC).

The second generation of electrical motors appeared at the beginning of the 20th century after the invention of first power electronic devices. They also based on well known synchronous and induction electromechanical converters, however they employ some electronics to form a rotating magnetic field. This rotating magnetic field can be discretely rotating (by steps) or continuously rotating. Well known electrical motor with a discretely rotating field is a stepping motor (STM) (for example, in a quartz-crystal clock). In the same group are brushless DC motors (BDCM) and switched-reluctance motors (SRM). A continuously rotating magnetic field is in a permanent magnet synchronous motors (PMSM) and in the vector controlled induction motors (VCIM). The second generation of electrical motors is broadly employed in computer hard and floppy drives, in printers, fax machines, robots etc. The operation of such motors is impossible without electronics.

The first generation (transducers, which can operate without electronics) contains potentiometers (PM) and resolvers (RS). The second generation of position transducers involves pulse encoders (PE) and absolute encoders (AE). They can't operate without any electronic devices. Speed transducers are called tachogenerators. They include DC tachogenerators (DCT), induction tachogenerators (IT) and synchronous tachogenerators (ST). The second generation is represented here only by a brushless DC tachogenerator. However, there are some other types of speed transducers with electronics.

The first generation of electrical machines is the subject of electromechanics. The second generation of electrical machines coupled with electronics is studied by the new science electrical mechatronics or electromechatronics. The electrical mechatronics is the branch of mechatronics, which is the synergetic integration of mechanical engineering with electronics and intelligent computer control.

Encoders

An encoder is a position transducer, which has the input shaft and output terminals, which produce the parallel or serial code of the shaft angle position φ.

The resolver contains an input (excitation) winding on the stator and sine and cosine windings on the rotor, which generate AC output voltages u_s and u_c with the envelopes $u_{s.en}$ and $u_{c.en}$. These envelopes change in accordance to sin and cosine forms (sinθ and cosθ). To extract the envelope $u_{s.en}$ or $u_{c.en}$ output voltages, a special circuit or a chip may be used. It is called a phase-sensitive detector (or rectifier). Then the envelop voltages come to analog-to-digital converter (ADC) of any digital controller. Controller's software executes the following operation:

$$\arctan(u_{s.en}/u_{c.en}) = \arctan[K_r u_{e.m}\sin\varphi/(K_r u_{e.m}\cos\varphi]=\arctan(\tan\varphi)= \varphi.$$

Hence, on the output we have the absolute code φ. An encoder with an absolute output code is called absolute encoder. An absolute encoder with a resolver has the top precision among all electromechanical encoders (approximately 5”). However it is very expensive. More cheap is a photoelectric encoder.

It has some disc with holes or a transparency, which is called the code mask. This code mask is on the input shaft with bearings. Near the code mask a light-emitting diode (LED) and a photodiode are placed. The light from the LED passes through any hole in the mask and generates the current pulse in the photodiode. Then this pulse is converted into the output angle code.

There are two types of an encoder: an absolute encoder and an incremental accumulate encoder. Absolute photoelectric encoder has the code mask with N tracks, where N – is the number of the code bits. The higher order track 1 produces the photodiode output pulse (bit 1) during 180 degrees while the lower-order track 3 generates four pulses during one revolution as it is shown in Fig. 8. Hence any disk angle position, for example, 160 degrees is corresponded to the definite code.

Incremental (or accumulate) encoder is more simple. It contains a pulse encoder and an electronics. The pulse encoder has only one track with the great number of holes on it. The electronics has the digital counter, which counts the number of the photodiode output pulses after some zero position (index pulse). Then this counter generates the output absolute parallel or serial code. The error of such encoder, which is called the resolution, is measured in the number of output pulses N during one revolution of the code mask.

For the best encoder such resolution may be till 10,000 ÷ 20,000. For 10,000 holes the error is approximately 2’ (~0.5 mrad). The encoder with one track is fit only for an unilateral rotation. Encoder for both directions of rotation has two tracks with the same numbers of holes, which are in the quadrature.

The majority of modern controllers commercially available for drives has two special inputs for the direct connection of two incremental encoders quadrature outputs. Hence any additional counter outside the controller is not needed.

The main disadvantage of every accumulate encoder is the possibility to lose an absolute code position after the voltage supply interruption. In such circumstances our drive has to return to the zero position and to restart its moving from this zero point again.

At present accumulative encoders are the most cheep and popular angular transducers for modern digital drives.

Brushless DC motors

Brushless DC motor (BDCM) has characteristics similar to a classic DC motor, however has no any mechanical commutator and brushes. They are replaced by electronics and a position sensor.

Approximately at the same time in 1836 another great scientist W.Sturgeon from Great Britain suggested the inverted DC motor, where armature winding is on the stator and the excitation permanent magnet is on the rotor. The mechanical commutator switches the armature current in accordance with the rotor position in such manner to produce the maximum value of the rotating torque.. In modern drives inverted DC motors are employed too, however more seldom then classic DC motors because they have more complicated mechanical commutator.

Let's replace this mechanical commutator by two devices: a rotor position sensor and an electronic commutator. The electronic commutator switches the armature current in accordance with the rotor position measured by the position sensor. Of course the position sensor have to be brushless because the whole motor is brushless.

Such rotor position sensor contains four Hole elements (sensors) HS1 – HS4. Each Hole sensor HS is a small semiconductor chip with four terminals, connected to the chip plane corners. First corner is energized by a DC supply, second and third corners are connected to the common (ground) wire and the last fourth corner is connected to the output terminal. If we will place such chip in a magnetic field perpendicular to the induction *B* direction then we will observe the output Hole's emf, which is equal to

$e_H = K_H i_s B_\perp$,

where i_s – the supply current, $B_\perp$ - the induction component along the axis perpendicular to the chip plane and K_H – the Hall's constant.

Let us place four Hall's elements in positions 1 – 4. One can design the motor electronic commutator, which will feed every coil in the rotor position, where the amount of the Hall's emf e_H will be near to the maximum value. In the rotor position shown in, a the maximum Hall's emf is observed for the Hall element HS1.

The main advantage of a BDCM is its brushless. However, it has some important disadvantages:

- a torque and hence a speed ripple,

1. a complexity due to an electronic commutation from a rotor position sensor.

In accordance with this equation to decrease the speed ripple we have to increase the load moment of inertia, to increase the motor speed and hence the gear ratio or to increase the number of stator coils (phases) which increase the number *n*. That is why 3-phased BDCM is more popular.

Calculations show that for common drives with a mechanical gear a BDCM speed ripple is permissible when the rated speed is some thousands rpm. Therefore, a torque and a speed ripple problem is important only for gearless (direct) drives where the speed ω is relatively small.

Stepping motors

Another brushless motor, which is very popular in mechatronic drives, is stepping motor. For example, such motor is employed in a computer floppy or hard drives for a disk track search.

Stepping motor has no any position sensor and is more simple than a BDCM. Such motors are very convenient for a computer control. However, they have two important disadvantages. Their rotation is not continuous but step-by-step. It can damage any mechanical gear or device. Besides a stepping motor can skip some of its input pulses and hence a real position will differ from the desired (reference) position. One can observe such stepping motor fault (a halt) if input pulses frequency will increase above any permissible level.

PWM amplifiers

Amplifier with pulse-width modulation (PWM) mode is a transistor amplifier with the high efficiency. The main disadvantage of a simple linear amplifier is the high power dissipation in every transistor. Hence a big heat sink is needed. To decrease such waste of energy a modern method for controlling voltage called pulse-width modulation, or PWM for short is employed.

Let us consider any n-p-n bipolar transistor with a pulse-width modulator (PWM) connected to the transistor base . The transistor collector is connected via the load R_L to the plus terminal of the DC voltage supply u_{cc} (sub "cc" means "continuous current"). The emitter is connected to the common (ground) wire. Let us consider that the input voltage u_1 is increasing from u_0 value in accordance with the linear law.

PWM is an electronic chip which converts a DC input voltage u_1 in an output impulse sequence or train u_2 with a constant chopping frequency f and period T=1/f=const. The pulse duration (width) T_s at the PWM output is proportional to the input voltage magnitude.

In the PWM output voltage we have two different regions. In the Region 1 when the positive voltage is applied to the base terminal during the time T_s the collector and the emitter are closed (the transistor saturation). Here the collector voltage with respect to emitter u_{ce}=0, all supply voltage is applied to the load and the collector current i_c = max. Conversely in the Region 2, the base voltage with respect to emitter is zero and we have the open switch (the transistor cutoff). Hence u_{ce}=u_{cc}. No voltage is applied to the load and i_c=0.

One can see that in both regions the power dissipated in the collector is zero $P_c=i_cu_{ce}=0$, because in the Region 1 u_{ce}=0 and in the Region 2 i_c=0.

Of course this is valid only for an ideal transistor. In a real transistor we have some power dissipation. However this power dissipation is much lower than that which occurs in linear operation.

The chopping frequency for a motor control is preferable from 1 to 20kHz. When the switching frequency is low the motor will have a sufficient torque ripple and produce a noise. This noise is not audible for the frequency higher than 16kHz. PWM-amplifiers are the most popular transistor drive amplifiers today.

Digital controller

Digital controller for a closed-loop drive can be built as an 8 or 16-bit microcontroller with two digital inputs and one output. First input is employed for the reference input code φ_1, while the second is for the feedback code φ_2 from a feedback encoder. Output error code can be converted in the error voltage by a digital-to-analog converter (DAC). The majority of the modern controllers converts an output error code directly in the pulse-width-modulated form to control directly power amplifier transistors. In Russia the most popular and available now are the next families of 16-bit microcontrollers: Intel MCS196 from Intel corporation, Siemens C166 from Infineon Technology company, Motorola DSP56800 from Motorola corporation.

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