Method for increasing the damping of an electro-hydraulic drive system of anthropomorphic walking robots

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Annotation. Due to the fact that anthropomorphic walking robots (AWR) are becoming one of the classes of extreme robotics tools, the task of creating drive systems that simultaneously have high indicators for a set of parameters arises. In particular, the problem arises of preventing the occurrence of self-oscillations in conditions where servo drives with high quality factor experience strong dynamic mutual influence through the actuator. According to the totality of indicators for AWR designed for operation in extreme conditions, electro-hydraulic servo drives are preferable. Features of the dynamics of the ASH actuators and the electro-hydraulic drives used on them force us to look for new ways to correct their dynamic properties. This article presents a method of reducing the propensity of a drive system to generate self-oscillations by correcting hydraulic drives using acceleration feedbacks. It uses an estimate of the relative accelerations of the robot links during movement using the signals from pressure sensors installed in the actuator hydraulic motor. The calculations are made using the equations of dynamics of the AWR actuator, taking into account the temporarily imposed external connections. The method allowed to significantly increase the dynamic accuracy of the drive system of the prototype AWR developed by MSTU N.E. Bauman.

Introduction

The fact that anthropomorphic walking robots (AWRs) are becoming one of the classes of extreme robotics is explained, among other things, by the fact that most of the emergency situations (accidents, catastrophes, fires), to eliminate the consequences of which robots have to be used, occur on artificial objects. Robots have to operate in an impenetrable environment, and in many cases it is an environment adapted for humans: narrow corridors, steep stairs, cabins and other rooms of various equipment.

To use AWR as a means of replacing a person when working in an environment adapted for a person, it is advisable that the kinematics (Fig. 1) and the weight and size parameters of the robot be comparable to human ones. This allows him to win in such conditions in efficiency in comparison with other means of extreme robotics [1, 2, 3]. If possible, it is advisable to reduce the mass of the robot. In the event of it falling on a person, the robot should not seriously injure him. It is also desirable that two people were able to lift the robot, so its mass should not exceed 100 kilograms.
I, — control current, $x_s$ — the displacement of the spool, $\Delta p_{HM}$ — the pressure difference in the cavities $HM$, $R_E$ — external load, $y_s$ — the movement of the rod $HM$, $W_{EHV}$ — transfer function of an electrohydraulic amplifier, $k_{Qx}$, $k_{qp}$ — the linearization coefficient of the expenditure flow and pressure drop characteristics of the spool, $E$ — volume modulus of elasticity of a liquid, $V$ — the volume of cavities $HM$, $F$ — piston area $HM$, $m$ — given to the stock $HM$ weight, $b$ — coefficient of viscous friction.

Fig. 1. Block diagram of an open electrohydraulic drive.

The executive system of extreme AWR works in severe external conditions, a set of conflicting requirements is presented to it.

1) Rigid weight and size restrictions on the parameters of the drives; a large number of drives (up to 30 or more) must be arranged in dimensions commensurate with human ones.

2) Limited energy resources; power and cable management seriously complicates the work of the robot in the emergency zone, although in some cases this is justified. At the same time, weight and size restrictions do not allow the use of a powerful on-board power source with a large supply of energy.

3) A large range of operating temperatures, since it is impossible to predict in advance the place and time of use of the AWR. For example, it is possible to use AWR in a fire.

4) Aggressive external environment; extreme AWR may be required to act during chemical and possibly radioactive contamination, and possibly under water.

5) The impact of vibration and shock; AWR can be delivered to the work site by various vehicles that are not always adapted for this. When acting near the object of work, there is a danger of collapse of structural elements of buildings and structures, falling from a height.

Under these conditions, the ASR executive system must perform complex and diverse tasks. Moving on a surface with a simple relief in marching mode, using dynamic walking or running, the robot should approach the object of work with a sufficiently high speed. In the rubble or in the presence of complex obstacles, a transition to static walking or climbing is possible (moving with the additional help of manipulators). The same modes of movement are advisable when performing work operations with objects of work.

When manipulating a work object, the executive system must move the grippers of the manipulators or the tools used in a predetermined way, or act on the work object with a given force, providing a given static and dynamic accuracy. As well as in the shutdown mode (the degree of mobility equipped with a drive turns into a simple hinge) or vice versa locks (the degree of mobility is "frozen"). Moreover, in the shutdown and lock modes, it is desirable to ensure minimum energy consumption or its absence.

An important role in choosing the type of drive for a robot designed for operation in extreme situations is played by specific power. Its minimum value can be estimated on the basis of the similarity of overall dimensions and characteristic work operations of a robot and a person.

It is generally accepted that an average person in terms of physical capabilities can develop a power of 100 W for a long time, a limited time of 300 W, and a peak maximum power of 1.2 to 2 kW [4].
is clear that these data are very arbitrary, since it does not stipulate what kind of work is performed, there is no binding to specific muscles. However, we can say for sure that continuous power is determined by the capabilities of the human energy system, and above all the cardiovascular component. When it is mentioned about peak power, they usually mean work done by the leg muscles (running, cycling).

Based on this, it can made an estimate of the total power of the main muscles of a person having their own analog drives in AWH. If it is assumed that the estimated movement is performed simultaneously by three sagittal degrees of one leg, then the total power of the corresponding muscles is approximately 0.1 of the total power of all muscles. Then the total (installed) peak power of the muscles of the average person is approximately from 12 to 20 kW. This power corresponds to the work of the muscles in the middle of their working characteristic, known as the Hill-Abbot Curve [4]. Such a concave characteristic is quite rare in the most common drives in technology. Therefore, for example, throttle hydraulic drives with the same maximum force and speed as the muscles, should have almost three times the maximum power, and electric drives with a linear inclined characteristic - two and a half or more.

According to the author’s estimates, made on the basis of experience with a prototype AWR created at MSTU. N.E.Bauman [5, 6], the total mass of the drives can be approximately 20% of the total mass of the robot. Therefore, in order for the ASR to have working capabilities comparable to at least a person average in physical development, the specific power of hydraulic drives should be more than 1.8 kW / kg, and electric drives together with gearboxes should be more than 1.3 kW / kg.

In addition to power, the drives must provide comparable idle speeds and braking moments. For example, it can given the following approximate estimate: the greatest braking torque is required to extend the knee joint (approximately 400 N ∙ m); the least braking torque is required to rotate the wrist around the longitudinal axis forearm (approximately 20 N ∙ m). The limiting angular velocities have a much smaller spread and are approximately 10 r / s in the most loaded joints, and 20 r / s in the least loaded.

It is extremely important to ensure sufficient dynamic accuracy of the drive system. Based on the analysis of the operation of the foot drives of the aforementioned AWR prototype model in the process of dynamic walking, the author obtained an estimate of the minimum required drive bandwidth of 10 Hz, and it should be ensured under conditions of strong interference through the robot's actuator.

Also, high energy efficiency and ease of control are required from the drives.

Based on the set of requirements, electro-hydraulic drives are best suited for the ASR executive system. Electro-hydraulic drives have a number of specific features, some of which are especially manifested in the complex AWR multi-link executive system. In particular, much more acute than for a single drive, the problem arises of ensuring high dynamic accuracy, and in conjunction with the problem of eliminating the risk of self-oscillations. Methods for solving this problem for electro-hydraulic drive systems also have their own specifics. One of the possible methods, which has shown its effectiveness in practice, is discussed below.

Methods

Executive systems are not only walking, but many other modern robots are complex controllable multi-link spatial mechanisms with many drives and a tree-like kinematic structure. They can have several tens of degrees of mobility. Drives installed in the degrees of mobility of such robots form a single multi-connected system. They experience significant interference through the actuator and a common energy source of limited power, therefore, it is advisable to control the drives with the help of a multi-connected controller. The modern theory of automatic control has many methods for the synthesis of such controllers, however, when creating systems for controlling the movement of walking robots, a lot of problems arise. In particular, the well-known “curse of dimensionality” makes the synthesis of regulators for systems with so many drives quite complicated and time-consuming even if the structure and parameters of the system are constant.

In AWR, the configuration of the actuator is constantly changing during movement. External additional mechanical bonds appear and disappear imposed on the links of the mechanism, primarily
on the feet. This is accompanied by impacts, the parameters of which can be predicted only very approximately. External loads and mass inertia characteristics of the actuator are changing. Therefore, it is necessary to continuously adapt the controller settings in real time, and in conditions when not all system parameters are available for direct measurement, and the corresponding signals from the sensors can be very noisy.

The task of controlling such a complex multidimensional, high-order, non-stationary drive system in practice is still difficult to solve. Therefore, a popular method for the synthesis of drive control systems, in which the drives are initially considered independent and calculated based on the worst combination of reduced masses (moments of inertia) and static loads. Further, the correction of the obtained solution is carried out according to the simulation results, taking into account the mutual influence of the drives, external communications and other operating features. In reality, this means a significant (often an order of magnitude) decrease in the quality factor of drives in terms of speed. The system in this case is not optimal, but it often allows us to solve practical problems.

In the case of AWR, this approach is applicable only when creating robots of very small sizes, usually toys. With an increase in the geometric dimensions of the robot, the temporal characteristics of motion, subject to similar conditions, also increase. The forces that mainly determine the movement of a walking robot are the forces of weight and inertia. Thus, subject to geometric similarity of actuators and kinematic similarity of movements, dynamic similarity is achieved when the Froude numbers are equal

\[ Fr = \frac{v^2}{gl} \]

Where \( v \) — robot speed,
\( g \) — acceleration of gravity,
\( l \) — some characteristic size of the robot, for example, its height.

Therefore, the temporal parameters of the movement, for example, the step period, increase in proportion to the square root of the linear size (for dynamically similar movements)

\[ T \sim \sqrt{l} \]

For example, a small anthropomorphic robot with a height of 0.3 m must walk almost 2.5 times more often to perform a movement similar to the normal walking of a person with a height of 1.8 m. Hence, many people have the illusion of ease of controlling the robot's dynamic walking (toys can!). In fact, if the walking periods are equal, the dynamic walking of a person can correspond to the static walking of a robot toy with relatively large feet, the implementation of which is fundamentally simpler.

As the robot's growth increases, the time characteristics of its Executive system also change. The robot's mass, all other things being equal (true for similar robots), is proportional to the cube of its linear size. Then the moments of inertia that characterize the Executive mechanism change proportionally to the fifth power of the linear size. Time constants of hydraulic drives, taking into account the volume of hydraulic cylinder cavities, their geometry and reduced moments of inertia, are proportional to the linear size of the robot

\[ T_{dr} \sim l \]

It follows that when the linear dimensions of the robot change, the ratio of time constants characterizing the dynamic properties of the drives and the temporal characteristics of the movement changes in proportion to the square root of the characteristic linear size. For example, if the same materials used proportionally increase all linear dimensions of the robot twice, the time constants of the drives will increase 20.5 times more than the temporal characteristics of the movements. This leads to the fact that, firstly, with an increase in the size of the robot, the dynamic accuracy of working out the required movements decreases, and secondly, the time constants of the drives approach the time
constants of the stabilization loop of the robot according to the signals of the orientation system, which reduces the quality of its operation.

This leads to the conclusion that you should not increase the linear dimensions of the AWR unnecessarily. You should also reduce the robot's weight by using light construction materials. This trend can be seen in the works of most AWR developers. The growth of most recently developed AWR is less than 2 m. Based on the experience gained in working with the layout model of the machine created with the participation of the author, we can recommend the robot's height in the range from 1.5 to 1.7 m. At the same time, the speed and dynamic accuracy of the robot's drive system are subject to strict, difficult-to-meet requirements.

The block diagram corresponding to the linearized equations of the mathematical model of a typical single-channel electro-hydraulic drive with throttle control and a symmetrical hydraulic cylinder is shown in Fig. 2. Modern electro-hydraulic amplifiers (EHAs) have high speed, due to which, in most cases, executive hydraulic motors (HM) together with mechanisms connected to the output link have a decisive influence on the dynamics of the drives. In this case, the damping is determined by the coefficients $k_{Qp}$ and $b$ (the coefficient of viscous friction in the hydraulic motor in total with the reduced total coefficient of viscous friction in the actuator). Moreover, $k_{Qp}$ is proportional to the displacement of the spool of the hydraulic amplifier, so when positioning the drive, the damping is reduced, and in the case of small leaks through the closed spool slits, it is mainly determined by friction in the gaskets of the HM. However, the friction parameters in the seals are not stable and depend on many factors that change during the operation of the drive: the pressure drop on the seals, the temperature of the working fluid, the condition of the working surfaces, and the degree of aging of the seal materials. In addition, to improve the accuracy of the drives, friction is minimized, which reduces damping. Even if we consider the idealized situation and when analyzing the dynamics of the drive, consider all other degrees of mobility frozen, when changing the configuration of the robot, the mass reduced to the main rod of the main cylinder and the load on the drive change. Accordingly, the frequency characteristics of the drive change. As a result, a certain region of the probable location of the top of the resonant peak of the drive on the LAH plane is formed (Fig.2).

![Fig. 2. LAFR view of the linear model of the power part of the hydraulic drive.](image)

The probability of the appearance of high peaks in the mid-frequency region of the LAH forces either to reduce the speed factor of the drive or to find dynamic correction methods to obtain the necessary phase and amplitude reserves. Introduction of damping speed feedbacks for hydraulic drives is ineffective. In aviation, for example, in a similar situation, hydro mechanical correction of dynamic pressure is used. A similar result can be achieved using electric feedback to accelerate the output link of the drive, measured relative to its body. However, in the case when the hydraulic motor is mounted on a moving base, for example, on a moving link of the AWR mechanism, this acceleration is difficult to measure. In systems with one degree of mobility in practice, as a rule, instead of acceleration, an estimate of its magnitude is used using signals from pressure sensors installed in cavities. This is easy to do, since in systems with one degree of mobility, the acceleration of the output link is proportional to the pressure drop up to the influence of external loads. That is, to assess the magnitude of
the acceleration, it is necessary to convert the pressure drop on the hydraulic motor into force (moment) at its output link and divide by the mass (moment of inertia) reduced to the output link. Moreover, the obtained value will depend not only on acceleration, but also on the reduced output link of the external load hydraulic motor. But this problem can be solved using the circumstance that for correcting the properties of the drive, the mid-frequency part of the spectrum of the received signal is required, and the influence of the external load mainly affects the low-frequency part of the spectrum. A correction device (high-pass filter) with a transfer function of the form is installed in the damping feedback loop

\[ W = \frac{T_s}{T_s + 1}. \]

Its time constant is chosen so that it reduces the influence of low-frequency vibrations and eliminates the influence of the constant component associated with external load, but leaves the signal unchanged in the mid-frequency region that determines the stability and dynamic properties of the drive. Figure 4 shows the corresponding block diagram, where \( k_F/m \) is the feedback coefficient for dynamic pressure, and \( k_a \) is the transmission coefficient for acceleration.

Fig. 4. Correction of frequency characteristics of an open drive using dynamic pressure feedback.

Using the method of inverse characteristics, it can be shown that as a result, the drive LAH will lie no higher than the ABC line (Fig. 5), which is a reflection relative to the horizontal axis of the LAH correction chain. Thus, the resonant peak, regardless of its location, will be "cut off".

Fig. 5. Correction of frequency characteristics of an open drive using dynamic pressure feedback.
However, this correction method is not directly applicable to multi-stage systems with a strong interaction of the drives through the actuator, which includes robots. In the case of AWH, additional difficulties are caused by the tree-like nature of the actuator, its lack of attachment to a fixed base, and the variability of external relations. The methodology of mathematical modeling of the dynamics of the executive system of AWR, worked out during the creation of a prototype AWR in MSTU. N.E. Bauman, described in [5, 6, 7, 8]. The method involves the use of a "fake" actuator to the absolute coordinate system of a fictitious kinematic chain, consisting of weightless links connected by three translational and three rotational degrees of mobility with zero hinge moments. As a result, the dynamics of the actuator of the robot is described by the following block-matrix equation:

\[
\begin{pmatrix}
I_{II} & I_{IR} & -J_I^T \\
I_{IR}^T & I_{RR} & -J_R^T \\
-J_I & -J_R & 0
\end{pmatrix}
\begin{pmatrix}
\dot{q}_I \\
\dot{q}_R \\
\end{pmatrix}
+ \begin{pmatrix}
H_I \\
H_R \\
-P \\
\end{pmatrix} = \begin{pmatrix}
0 \\
\tau \\
0
\end{pmatrix}
\]

Where \( I_{II}, I_{IR}, I_{RR} \) — components of the inertia matrix of the actuator of the robot;

\( J_I, J_R \) — components of the Jacobi matrix, which is part of the equations of relations superimposed on the actuator (for example, on the supporting foot), and expressed relative to accelerations; this matrix also establishes the relationship between the reactions of superimposed bonds and the components of the hinge moments caused by these reactions;

\( P \) — a column matrix constituting the right-hand side of the equations of relations expressed with respect to accelerations;

\( R \) — a column matrix containing a vector of reactions of superimposed external relations;

\( \ddot{q}_I, \ddot{q}_R \) — components of a matrix-column containing a vector of generalized accelerations of the mechanism;

\( H_I, H_R \) — components of the matrix-column of reduced external, centrifugal and Coriolis forces;

\( \tau \) — vector of hinge moments (forces) developed by drives.

In this equation, the submatrix indicated by the index I refers to the fictitious kinematic chain, and the index R refers to the real links of the mechanism. An efficient procedure for calculating matrix elements of this equation adapted to tree mechanisms is described in [5, 7]. The Jacobi Matrix J has as many rows as there are additional external links imposed on the Executive mechanism. For example, if the robot is stable on one leg, and translational and rotational connections are superimposed on all three axes, then the matrix J contains 6 rows, and if the robot is standing on two legs, then 12 rows.

Since the elements of the Ni matrices depend on the current values of generalized speeds, these values are small at low speeds, and even more so when stopping in place, and in some cases they can be ignored. Ignoring also the external forces applied to the mechanism, with their predominantly low-frequency spectrum (except for coupling reactions), the equations of dynamics of the robot's Executive mechanism can be written in simplified form:

\[
\begin{align*}
I_{II} \ddot{q}_I + I_{IR} \ddot{q}_R - J_I^T R &= 0 \\
I_{IR}^T \ddot{q}_I + I_{RR} \ddot{q}_R - J_R^T R &= \tau \\
J_I \ddot{q}_I + J_R \ddot{q}_R &= 0
\end{align*}
\]

At low speeds and when the robot is stopped, the spool in the electrohydraulic drive amplifiers are at zero or offset by a small amount, which directs the coefficient to zero \( k_{Qp} \) in a linear mathematical model of the drive, and exacerbates the problem of providing sufficient damping of the drives to prevent self-oscillation.

The author suggests using the above simplified form of the equation to determine the approximate values of relative accelerations in the degrees of mobility of the robot according to the measured in
the process of movement of the robot arm torques (forces) and loads on the robot's feet. Hinge moments (forces) are determined during the robot's movement by the measured values of pressure in the cavities of hydraulic motors, just as in the case of single-channel hydraulic drives. Forces and moments on the robot's feet are measured during movement using six-component force-moment sensors installed on its feet. The obtained values of τ and R allow us to calculate approximate values of generalized accelerations. To do this, the above system of equations is proposed to be represented as a matrix expression:

\[
\ddot{q}_R \approx (I_{RR} - I_{II}^{-1} I_{IR})^{-1} (\tau + (J_{IR}^{-1} - I_{II}^{-1} J_{II}^{-1}) R)
\]

The acceleration estimates obtained from it can be used to dampen the robot's drive system in the same way as it is done in single-channel electrohydraulic tracking drives. Accordingly, to reduce the influence of external forces that load the drives, as well as in single-channel hydraulic drives, it is needed to use high-frequency filters.

One of the advantages of this method is that there is no need to change the calculation algorithm when changing the movement phases corresponding to the change of the robot's support legs. In this expression, it can be included equations of connections that are imposed on both feet at once. They will be activated when the corresponding reactions appear, measured by sensors installed on the robot's feet.

**Conclusion**

This method was used in the control system of the prototype ASR model and allowed to increase the quality factor of its speed by 3 ... 10 times. Due to this, the dynamic accuracy of the drives has increased to a level sufficient to implement the dynamic walking of the robot.

In the Figure 6 shows experimental curves illustrating the effect of the depth of damping feedback on the quality of the drives. During the experiment, the robot stood on its right foot.

**Fig. 5.** Transient processes in the knee drive of the AWR at various settings of feedback on dynamic pressure.
A rectangular signal with an amplitude of 0.05 rad was applied to the input of the knee drive of the raised left leg. The input action and response of the drive were recorded with three damping feedback settings. The average process was obtained with damping bond coefficients close to optimal. The upper one — with an increase in the damping feedback coefficients in all drives by 5 times, and the lower one — with their decrease by 4 times. This experience illustrates the existence of an optimal setting and the impossibility of a system functioning with a given speed factor without additional damping. It can be stated the stability of the system to change settings over a wide range.

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