Robust automatic control system of vessel descent-rise device for plant with distributed parameters “cable – towed underwater vehicle”

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Abstract. The paper is devoted to a problem of synthesis of the robust control system for a distributed parameters plant. The vessel descent-rise device has a heave compensation function for stabilization of the towed underwater vehicle on a set depth. A sea state code, parameters of the underwater vehicle and cable vary during underwater operations, the vessel heave is a stochastic process. It means that the plant and external disturbances have uncertainty. That is why it is necessary to use the robust theory for synthesis of an automatic control system, but without use of traditional methods of optimization, because this cable has distributed parameters. The offered technique has allowed one to design an effective control system for stabilization of immersion depth of the towed underwater vehicle for various degrees of sea roughness and to provide its robustness to deviations of parameters of the vehicle and cable’s length.

1. Introduction
The influence of sea waves is a result of need to use special vessel devices for heave compensation of towed vehicles during the underwater operations [1].

For more efficiency of underwater operations, it is offered to realize a heave motion compensation system as a descent-rise device with a nodding boom. The deviation of underwater vehicle’s immersion depth caused by the vessel heave can be compensated by changing an angle boom. And the height of the nodding boom’s head remains invariable to the plane of the undisturbed sea surface. The derricking nodding boom is equal to cable’s length and underwater vehicle’s weight set during a change. In such a way, it is possible to stabilize the vehicle on a sea surface and to eliminate slack or dangerous dynamic strain in the cable [2].

Synthesis of the automatic control system includes definition of its structure, i.e. the list of the sensors, measured outputs, the number of the correcting devices and their connections and also calculation of the controller parameters.

2. Methods
The automatic control theory considers automatic control systems in a representation of the time domain state space. These are MIMO systems. Often the task of control consists in definition of a feedback coefficients matrix which provides desirable properties to the feedback control system. The outputs of the plant are measured by sensors or observers [3].

Any practical engineering problem of designing of the automatic control system is complicated by
the fact that in the plant model and in the knowledge of input disturbances received on the basis of the
theory or as a result of identification, there is an uncertainty (or error) resulting in their difference from
real technical systems. So, the model "cable-underwater vehicle” system is considered as linearized
with constant coefficients, but in fact is nonlinear with variable parameters. The motion resistance
force of the vehicle and cable depends nonlinearly on the speed. There are also other unaccounted
nonlinearity and the fast time constants causing unaccounted dynamics. The weight of the vehicle
changes during underwater operations. It depends on the weight of load which the manipulator lifts or
lowers. In addition, the coefficient of entrained water changes depending on immersion depth of the
underwater vehicle. The stochastic processes of the vessel heave and sea waves also add uncertainty to
the description of system behavior.

As is known, linear quadratic control methods have essential disadvantages. Experience has shown
that when solving specific technical problems, the optimum systems, synthesized in a such way, are
sensitive to parameters of the real plant model and to characteristics of external disturbances. Such
systems are non-robust. These systems become not only non-optimal but also a failure if aprioristic
information about the plant and the external environment is known not precisely or parameters of the
system differ from the nominal. It is possible for many reasons.

There is need to formulate and solve a synthesis problem taking into account inaccuracy of
information about a plant and disturbances. The purpose of synthesis is providing stability of the
feedback control system with use of the single controller. This problem has to be solved not only for
the nominal plant (without model error), but also for any perturbed plant, which belongs to a set an
uncertainty class.

H-infinity methods are used in control theory to synthesize controllers for MIMO closed-loop
systems. Use of $H_\infty$-norm as a criterion of optimality during synthesis of MIMO systems is based on
the fact that $H_\infty$-norm is a value of the system’s gain. The H-infinity norm of the transfer function is
energy of a system’s output for a unit energy input signal. If the output is the system’s error, and the
system’s input is disturbance, then the energy of error is minimized for the worst case of input
disturbance when H-infinity norm of the transfer function is minimized. For SISO systems, this is
effective in the maximum magnitude of the frequency response [4].

The main feature of $H_\infty$-controllers is the fact that only aprioristic information about possible
external disturbances for robust control systems is used. The information about uncertainty is not used
at all. It leads to the fact that robust systems have to remain efficient (to have robust stability and the
set quality) at any limited disturbances at any time, i.e. the controller is always ready for the worst
case. However it causes also the main disadvantage of H-infinity systems, which is their considerable
conservatism.

The theory of robust systems is offered to be used during synthesis of the automatic control system,
but without use of traditional methods of their optimization. Application of these methods is very
complicated because the plant "a cable – vehicle” has the distributed parameters, and transcendental
functions are used for its description. The analysis of the automatic control system has to give an
answer to a question of a possibility to meet requirements at constant values of controller’s parameters
or to show need for system’s adaptation during change of parameters of the cable and the underwater
vehicle.

3. The controller’s synthesis
For operation of the descent-rise device as the compensator, it is offered to calculate controller
parameters so that changes of coordinates of the cable’s upper end to coordinates of the heave vessel
would correspond to processes in the low-pass filter. Such filter passes only those frequencies which
are lower of the first resonant maximum of the frequency response for the system with the longest
cable (10 km) (curve 1 in figure 1). Then the calculated controller parameters are independent neither
of external disturbances, nor of cable length. That is why, the designed control system is robust for
these disturbances.

The frequency responses of the designed filter (curve 3), a “cable – vehicle” system (curve 1) and
the ideal filter (a curve 2) are shown in figure 1.

The designed controller provides integrated regulation for the best adaptation of the control system to slow disturbances (for example, sea currents) and changes of vehicle’s weight [3]. Thus, the control signal, equivalent to the electric drive’s electromagnetic torque, consists of some components:

$$\frac{T_p(s)}{x_2(s)} = \frac{c_4 \cdot s^4 + c_3 \cdot s^3 + c_2 \cdot s^2 + c_1 \cdot s + c_0}{s + \frac{1}{s + d^2}}.$$  

The first component depends on the difference between reference and actual values of a derricking nodding boom angle (coefficient c1). The second component is proportional to the integral of this difference (coefficient c0). The third component is proportional to the angular speed of the derricking nodding boom (coefficient c2), and the fourth – to angular acceleration of the derricking nodding boom, i.e. to the output signal of the differentiating filter (coefficient c3). It is possible to receive the fifth component (coefficient c4) for faster transients. It is a derivate of angular acceleration, this is an output signal of the second order differentiating filter. The low-pass filter is connected to output of the controller.

**Figure 1.** Frequency responses: 1 – for a “cable – vehicle” system; 2 – for an “ideal filter”; 3 – for a designed filter.

4. The uncertainty of the plant caused by the cable

For the considered system, it is offered to consider uncertainty as multiplicative. Then the transfer function of the perturbed plant will be defined:

$$G(s) = G_0(s) \cdot (1 + \Delta(s)),$$

where $\Delta(s)$, $G_0(s)$ – transfer functions of the disturbance and an unperturbed plant [5].

In this case, the unperturbed plant is a system with a short cable (the distributed parameters are not considered) and nominal parameters of the cable and the vehicle. The transfer function of disturbance is the irrational transfer function containing information about the distributed parameters of a cable and deviations of cable’s and a vehicle’s parameters from nominal.

Such approach will allow one to estimate properties of the perturbed plant as during the parametric disturbances (during change of parameters), and during unstructured disturbances (influence of a cable).
5. Stability of the automatic control system with long cable

It is impossible to estimate stability of the automatic control system with a long cable by algebraic methods because of existence of transcendental functions in the description of the plant. Assessment by means of frequency criteria is complicated since Mikhaylov and Nyquist plots are infinite spirals. Therefore, it is offered to use a method of robust control. According to the chosen criterion, if an unperturbed closed-loop system is steady, then for stability of the perturbed system it is required that:

\[ |\sigma_0(j\omega)\| |\Delta(j\omega)| < 1, \forall \omega. [5]. \]

The analysis has shown that with nominal parameters of the cable and the vehicle, the control system is steady for any cable’s length.

The system with the cable’s length up to 6 km is stability for the cable, and vehicle parameters range down from nominal (to 50 %) and up from nominal (to 100 %).

6. The efficiency estimation of the control system with a long cable

A quality estimation of the synthesized automatic control system with a long cable can be given if one considers a sensitivity function. These are transfer functions, for which outputs are vertical displacements of the cable’s upper end and the underwater vehicle, and input is vessel heave.

Estimation was made for such cases as:

- the various cable’s length (up to 6 km);
- the deviations of cable’s and vehicle’s parameters in the range of ±50 %;
- the various sea state code causing the vessel heave.

The curves are shown in figures 2, 3.

The analysis has shown:

1. When the cable is longer, the control system is more sensitive to resistance coefficient’s decrease.
2. The heave influence is less if one increases vehicle’s weight for the plant with a short cable and increases the resistance coefficient for the plant with a long cable.
3. The sea state code is more, the range of cable’s lengths is wider, for which influence of vehicle’s weight remains more significant for decreasing vehicle’s immersion depth and deviations of the cable’s upper end position. This effect is explained by the fact that during an increase of the sea state code, the resonant maximum of the sea wave spectrum, the roll and heave spectrum are displaced to the area of the lower frequencies. The magnitude ripple of the “cable – descent-rise device – underwater vehicle” system is displaced to the area of higher frequencies and their amplitudes increase during a decrease of the resistance coefficient.

![Figure 2. Standard deviations of cable’s upper end position for sea state code 3 (a) and sea state code 4 (b): black lines – cable’s and vehicle’s weight up to 50 % from nominal, and vehicle’s motion resistance coefficient down to 30 % from nominal; light grey lines – for nominal cable’s and vehicle’s parameters; grey lines – cable’s and vehicle’s weight down to 50 % from nominal.](image-url)
and vehicle’s motion resistance coefficient up to 30 % from nominal.

![Diagram](image1.png)

**Figure 3.** Standard deviations of vehicle’s position for sea state code 3 (a) and sea state code 4 (b): black lines – cable’s and vehicle’s weight up to 50 % from nominal, and vehicle’s motion resistance coefficient down to 30 % from nominal; light grey lines – for nominal cable’s and vehicle’s parameters; grey lines – cable’s and vehicle’s weight down to 50 % from nominal, and vehicle’s motion resistance coefficient up to 30 % from nominal.

4. The received standard deviations of the vehicle’s immersion depth and the cable’s upper end positions for any sea state code are close that demonstrates the control system invariance to external disturbances from the announced class.

5. The descent-rise device reduces vertical displacements of the cable’s upper end of a vehicle (with a wide range of its operative parameters) in ten times for any sea state and with fixed controller’s parameters.

7. **Sensitivity control system with long cable**

The sensitivity function for the considered system is the descent-rise device’s force in the vessel heave compensation mode for vehicle’s immersion depth stabilization. The force value is calculated for a cable of various length (up to 6 km), with a deviation of cable’s and vehicle’s parameters (at a range of ±50%) and for various intensity of the sea wave causing the vessel heave (sea state code 3-5).

Calculations have shown:

1. For the cable’s length of up to 1.5 km, the descent-rise device’s force is greatest for the case of using the vehicle with nominal parameters.

2. For the plant with a long cable, the greatest force of the descent-rise device takes place during a decrease of vehicle’s weight and during an increase of its resistance coefficient. And contrariwise, the smallest force of the descent-rise device takes place during a decrease of resistance coefficient and during an increase of vehicle’s weight for the plant with a long cable.

3. For sea state code 3 and for the plant with the cable’s length up to 800 m and more than 5.5 km, the greatest force of the descent-rise device takes place during a decrease of resistance coefficient and during an increase of vehicle’s weight. For sea state code 4, such effect is observed for the cable’s length up to 1 km and more than 7 km, and for sea state code 5 – for the cable’s length up to 1.5 km and more than 9.5 km.

4. The maximum deviation of descent-rise device’s force does not exceed 1 % with any parameters disturbances from the specified range.

5. Increase of the sea state code from 3 to 4 leads to an increase of the maximum force of the descent-rise device by 21.5 %, and for sea state code 5 – by 62.6 %.
8. Conclusion
Thus, the offered technique has allowed one to design an effective control system for stabilization of immersion depth of the towed underwater vehicle for various sea state codes and to provide its robustness to deviations of parameters of the vehicle and cable’s length.

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