July 14, 1970 R. D. BERRY ETAL 3,520,263

CONSTANT DEPTH BUOYANCY SYSTEM

Filed Sept. 16, 1968 2 Sheets-Sheet 1

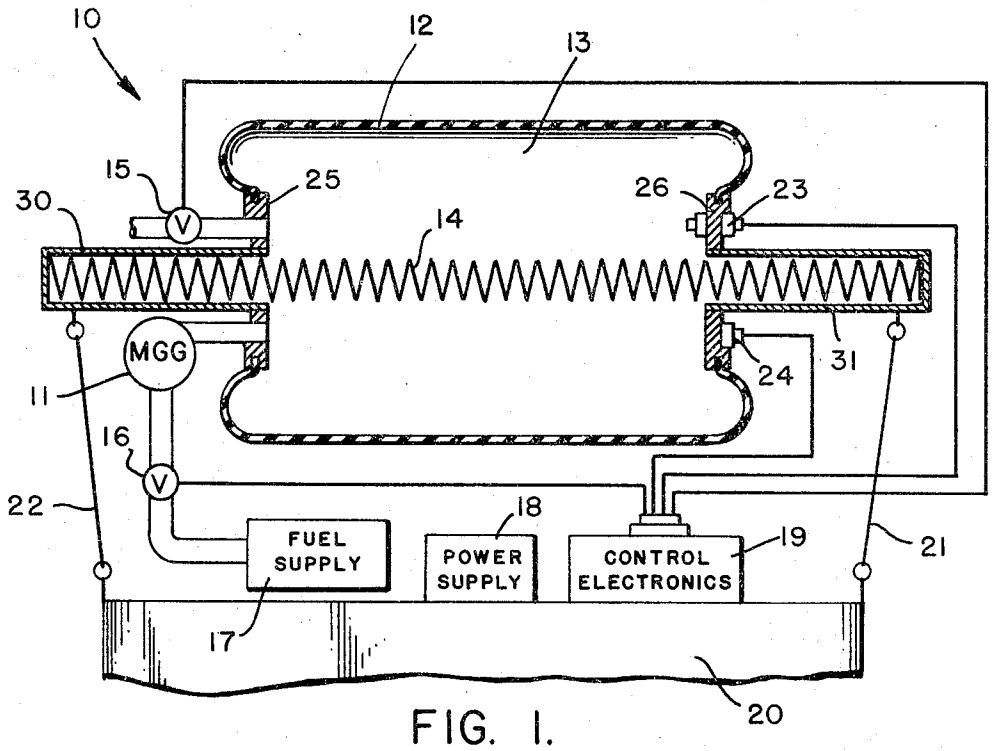

FIG. 1.

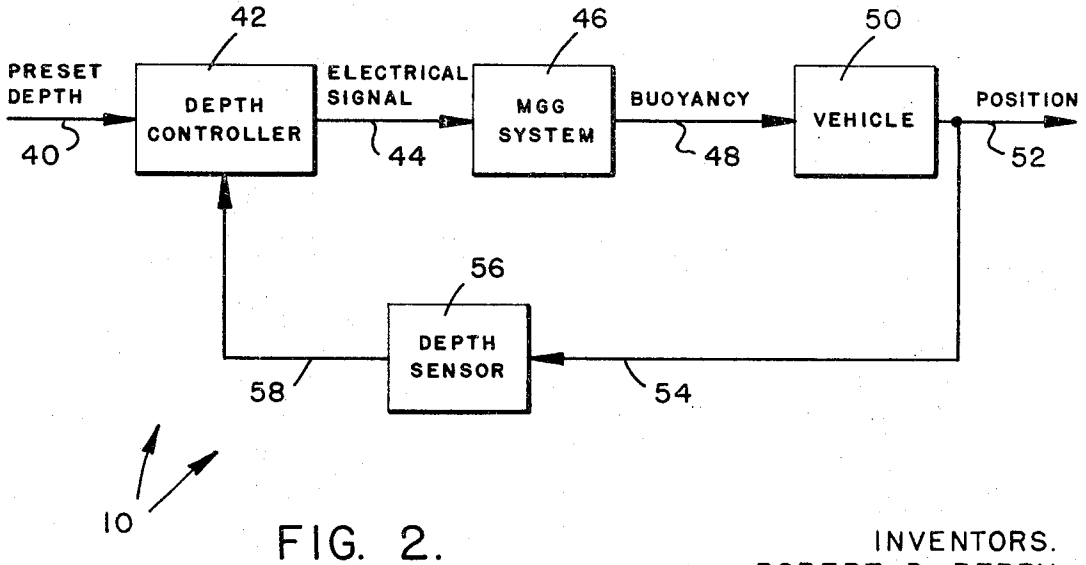

FIG. 2.

INVENTORS.
ROBERT D. BERRY
JAY WITCHER
ROY MILLER
ATTORNEY.
GERALD F. BAKER
AGENT.

CONSTANT DEPTH BUOYANCY SYSTEM

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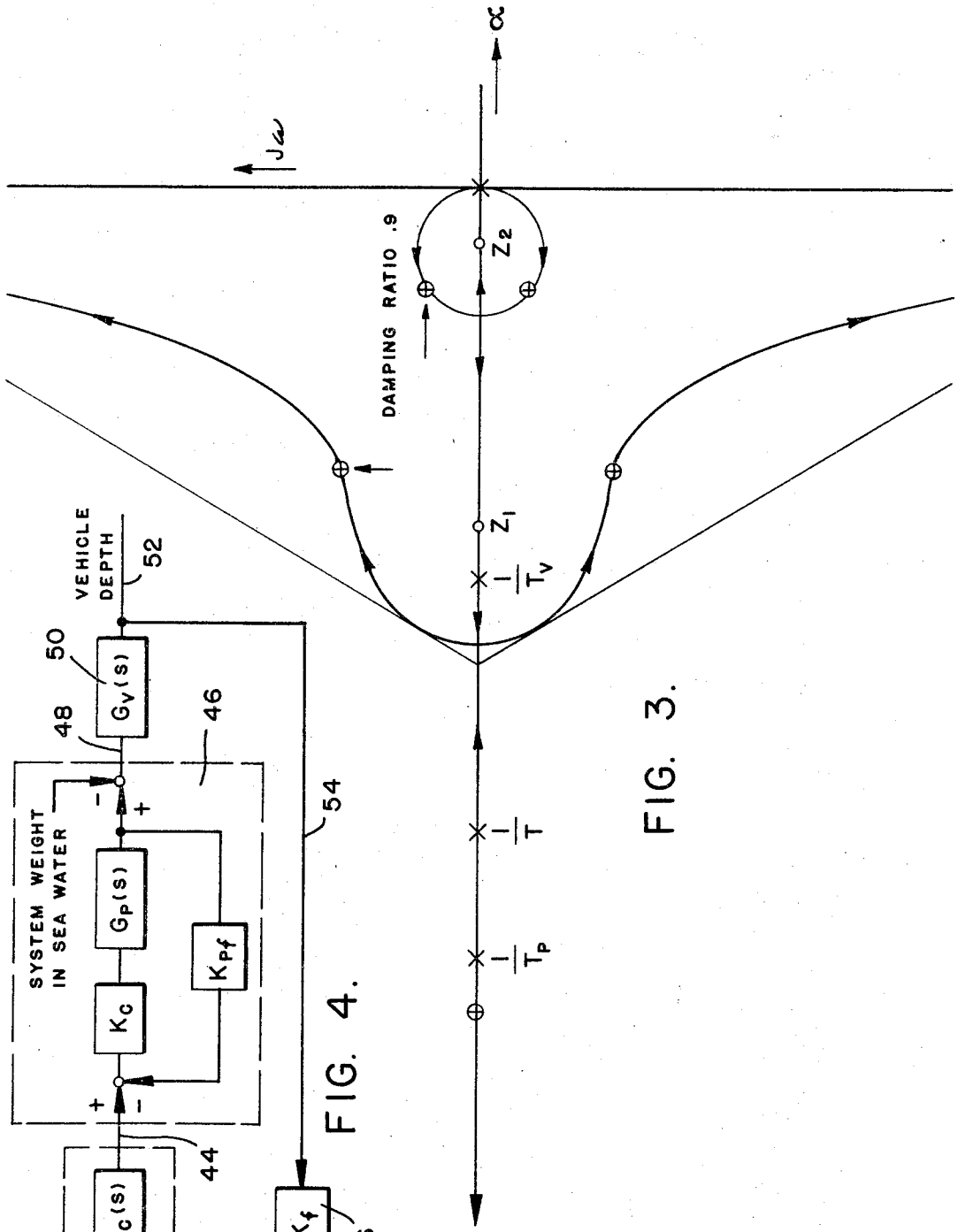

FIG. 3.

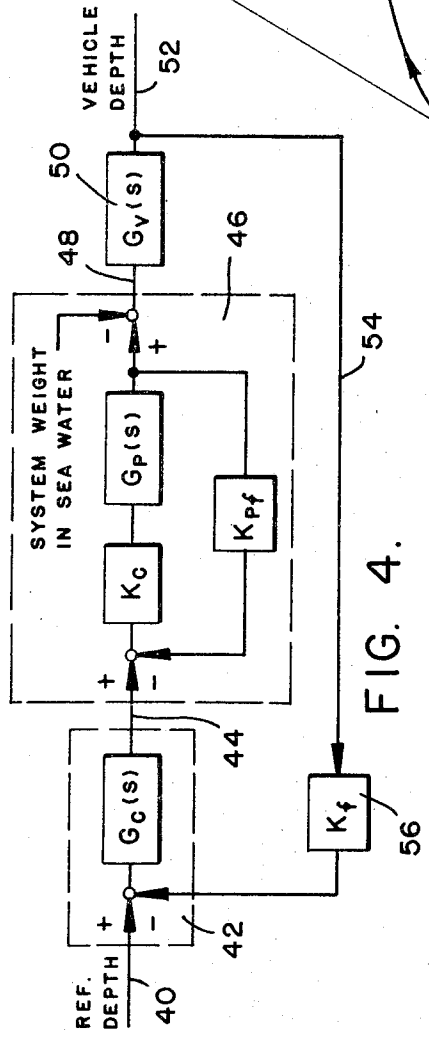

FIG. 4.

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CONSTANT DEPTH BUOYANCY SYSTEM

Robert D. Berry and Jay Witcher, China Lake, Calif., assignors to the United States of America as represented by the Secretary of the Navy

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Int. Cl. B63g 8/14
U.S. Cl. 114—16 1 Claim

ABSTRACT OF THE DISCLOSURE

A constant depth control system for an ocean vehicle is provided which maintains a constant depth by adjusting the displacement of a rubber gas bag to achieve neutral buoyancy when a feed back pressure equals a reference pressure. The displacement of the gas bag is related to the differential pressure between the gas inside the bag and the water outside the bag. Rate feed back is electronically controlled so that when a design depth (sea pressure) is approached, bag displacement is automatically adjusted to reduce the velocity of the system. The system may be adjusted to be neutrally buoyant and at zero velocity at the precise time that a preset reference sea pressure is reached.

GOVERNMENT INTEREST

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

For purposes of oceanographic study and exploration it is sometimes desirable to send a vessel to a predetermined submerged depth and to maintain the vessel at that depth.

Numerous systems have been suggested for effecting depth control by adjusting the buoyancy of a vessel including dropping ballast or releasing buoyant material; pumping water in and out of buoyancy tanks; and hovering controls by means of mechanical and fluid thrust devices.

The present invention relates to an improved system which maintains a constant depth of a vehicle by adjusting the displacement of a rubber gas bag to achieve neutral buoyancy when a predetermined reference pressure is equaled by feed-back pressure. The displacement of the gas bag is related to the differential pressure between the gas inside the bag and the water outside the bag.

The system according to the present invention is very stable and can be set to remain at a predetermined depth. The system does not require forward vehicle motion in order to maintain depth. Fuel may be supplied by a gas blow down system, pump or self pressuring fuel system.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

FIG. 1 is a diagrammatic view of one embodiment of the system;

FIG. 2 is a schematic of the system of FIG. 1, indicating the mode of operation;

FIG. 3 is a root locus plot of the system; and

FIG. 4 is a mathematical block diagram of the system.

DETAILED DESCRIPTION OF THE INVENTION

The system **10** shown in FIG. 1 comprises a flexible gas bag **12** consisting of rubber or the like. The gas bag shown is of cylindrical configuration with the ends of the cylinder confined by attachment of two circular end plates

25, 26. The end plates are biased toward the center of the bag **12** by means of a tension spring **14**. Spring **14** is fastened to the end plates **25, 26** by means of tubular guides **30, 31**, respectively. The amount of gas **13** in gas bag **12** may be decreased by the opening of vent valve **15** or increased by supplying fuel from supply tank **17** to a monopropellant gas generator **11** by opening valve **16**. Valves **15** and **16** may be electrically controlled from an electronic control center **19**. Control center **19** is adapted to receive signals from a differential pressure transducer **23** and a sea pressure transducer **24** and to relate signals to a preset parameter representative of the pressure calculated for the desired depth to be maintained. A pay load **20**, as well as other components such as the power supply **18** and the control section **19**, may be hung from the guides **30, 31** by means of hangers such as **21, 22**. It may be assembled with a minimum of effort and cost from hardware similar or identical to the hardware being tested for the Underwater Gas Generator programs now being conducted. Major components would include:

(a) Pressurized hydrazine fuel tank **17**
(b) Monopropellant gas generator (MGG) **11**
(c) Flexible rubber gas bag **12** with rigid end plates **25, 26** pulled together with a heavy coil spring **14**
(d) Two solenoid valves **15, 16** for filling and venting the gas bag **12**
(e) Power source (battery) **18**
(f) A differential pressure transducer **23**
(g) A sea pressure transducer **24**
(h) Control electronics **19**
(i) Rope of sufficient length to recover system

Items (a), (b), (c), and (i) may be found among items procured for the Navy deep sea recovery tests. Items (d), (e), (f) and (g) are off-the-shelf items. The only item that needs to be custom fabricated is item (h), the control electronics.

The system maintains a constant depth by adjusting the displacement of the rubber gas bag to achieve neutral buoyancy when the feedback sea pressure equals the reference pressure. The displacement of the gas bag is related to the differential pressure between the gas inside the bag and the water outside the bag. The differential pressure is a function of the spring extension. As the bag fills with gas, the spring is extended creating more spring force which in turn requires a greater differential pressure to balance the greater spring force. If the bag vent valve is opened the gas escapes causing a reduction in spring extension and differential pressure. If the system should sink below the design depth (sea pressure) the control system would call for a greater differential pressure between the gas and water which would cause the fill valve to open sending hydrazine fuel into the monopropellant gas generator. The fuel would decompose into gas and enter the gas bag causing an extension of the spring and subsequent rise in differential pressure. This should cause positive buoyancy and a gradual rising of the system. The control electronics includes rate feedback so that as the design depth (sea pressure) is approached the bag displacement is adjusted to reduce the velocity of the system. If the control system is properly designed the vehicle should be neutrally buoyant and at zero velocity at the precise time that reference sea pressure is reached.

Reference is now made to FIGS. 3 and 4 wherein the following reference symbols are utilized for brevity of explanation.

$G_c(s)$=Depth controller transfer function
K_c=Buoyancy controller transfer function
$G_p(s)$=Gas bag and associated hardware transfer function

K_{pf}=Gas bag volume feedback transfer function
$G_v(s)$=Vehicle dynamics transfer function
K_f=Depth feedback transducer transfer function

The heart of the system is the gas bag-MGG buoyancy control system which is the inner control loop of the block diagram including $K_c(s)$, $G_p(s)$, and K_{pf}. Earlier analog studies of a nearly identical system for the Navy's Moray vehicle indicated that there was no particular problem associated with stabilizing the buoyancy system at a constant depth. For a constant depth, the closed loop transfer function of the inner loop can be approximated by

$$\frac{k_p}{1+T_p s}$$

because

$$PV=MRT$$

$$V=MRT/P$$

R, T, P are nearly constant for a vehicle at constant depth.

$$M=\int \dot{M}_{in}-\dot{M}_{out})\,dt$$

$$V=k\int \dot{M}\,dt=k\frac{\dot{M}}{s}$$

$$G_p(s)=\frac{V}{\dot{M}}=\frac{k}{s}$$

$$\text{The closed loop transfer function}=\frac{K_c G_p(s)}{1+K_{pf}K_c G_p(s)}$$

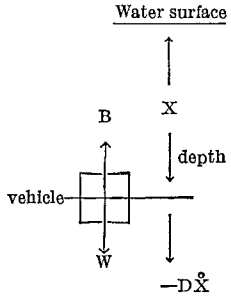
$$=\frac{\frac{K_c k}{s}}{1+\frac{K_{pf}K_c k}{s}}=\frac{k_p}{(1+T_p s)}$$

where

$$k_p=\frac{K_c k}{K_{pf}K_c k}=\frac{1}{K_{pf}}$$

$$T_p=\frac{1}{K_{pf}K_c k}$$

$G_v(s)$ is determined from the basic equations of motion, $F_x=ma_x$



W=weight of system in water
B=buoyancy force
D=drag coefficient

$$F_x=W-B-D\dot{x}=m\ddot{x}$$
$$=W(s)-B(s)-DsX_{(s)}=ms^2X_{(s)}$$

The drag force is assumed proportional to the velocity for small $\dot{x}$

$$G_v(s)=\frac{X(s)}{B_{(S)}-W_{(S)}}=\frac{-1}{s(D+ms)}$$
$$=\frac{-K_v}{s(1+T_v s)}$$

where

$$K_v=1/D$$
$$T_v=m/D$$

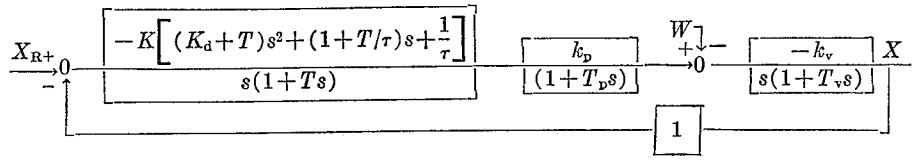
Assume $G_c(s)$ is a proportional plus reset plus rate controller with the following transfer function.

$$G_c(s)=-K\left(1+\frac{1}{\tau s}+\frac{K_d s}{1+Ts}\right)$$
$$=\frac{-K\left[(T+K_d)s^2+(1+T/\tau)s+\frac{1}{\tau}\right]}{s(1+Ts)}$$

where

K=proportionality constant
τ=integration rate time constant
Kd=derivative constant
T=derivative filter time constant

The block diagram is now



The forward transfer function, G(s), is

$$G(s)=\frac{Kk_p k_v\left[(K_d+T)s^2+(1+T/\tau)s+\frac{1}{\tau}\right]}{s^2(1+Ts)(1+T_p s)(1+T_v s)}$$

It would be desirable to choose the controller parameters in such a way that zeros occur between the dominant poles of the system transfer function, $s=0$, and

$$s=-1/T_v$$

The buoyancy system time constant should be much smaller in all instances than the vehicle's, i.e.,

$$1/T_p \ll 1/T_v$$

For non-oscillatory response the zeros should be real. A good response can be achieved by selecting $K_d=T_v$ and $\tau=8T_v$. The zeros then occur at

$$S_{0_1}S_{0_2}=-\frac{\left(1+\frac{T}{8T_v}\right)\pm\sqrt{\left(1+\frac{T}{8T_v}\right)^2-\frac{4}{8T_v}(T_v+T)}}{2(T+T)}$$

Expanding the terms in the square root

$$\left(1+\frac{T}{8T_v}\right)^2-\frac{4}{8T_v}(T_v+T)=1+\frac{T}{4T_v}$$
$$+\frac{T^2}{64T_v}-\frac{1}{2}-\frac{T}{2T_v}=\frac{1}{2}-\frac{T}{4T_v}+\frac{T^2}{64T_v}$$

Therefore

$$S_{0_1}S_{0_2}=-\frac{1+\frac{T}{8T_v}\pm\left(\frac{1}{2}-\frac{T}{4T_v}+\frac{T}{64T_v}\right)}{2(T_v+T)}$$
$$=-\frac{1.5-\frac{T}{8T_v}+\frac{T^2}{64T_v}}{2(T_v+T)}-\frac{.5+\frac{3T}{8T_v}-\frac{T^2}{64T_v}}{2(T_v+T)}$$

T should be chosen less than T_v and should be small enough that both zeros are still negative real numbers.

In FIG. 3 is shown the root locus plot of the system. Since the endurance of the system is a function of fuel used, the primary consideration in the design of a long duration control system would be minimization of fuel consumption.

The response time of the system would not be a design consideration since no depth command changes would be desired. A very stable system with a high damping ratio would be ideal. The highest damping ratio that can be achieved for the system with the root locus of FIG. 3 is 0.9. A lower gain would result in a pole closer to the origin on the circle touching the origin. Therefore the angle formed by the line from that new pole to the origin and the negative real axis would be larger thus the damping ratio would be less. A *higher* gain would result in a pole further away from the real axis on the other branch of the locus. The angle between the line from this new pole to the origin and the negative real axis would be larger thus the damping ratio would be less. The location of the poles for the optimum gain are shown on the root locus plot.

What is claimed is:

1. A constant depth buoyancy system comprising:

flexible container means adapted to be compressed to a minimum internal volume and extended to a maximum internal volume;

said flexible member being substantially cylindrical and comprising a peripheral wall of rubber-like material and two end walls; and biasing means between said end walls biasing said end walls toward a central position;

means for introducing a gas into said container under pressure;

means for exhausting gas from said container;

said means for introducing gas into said container comprising:

a monopropellant gas generator;

a fuel supply attached to said container;

first valve means between said fuel supply and said generator for supplying discrete amounts of fuel to said gas generator;

second valve means for exhausting gas from said container;

sensing means producing a first output representative of pressure external of said container;

second sensing means producing a second output representative of the differential between pressure within said container and pressure external of said container;

rate feedback means for producing a third output representative of the velocity of the system; and

means responsive to said first, second and third outputs for controlling said valve means for introducing fuel and for exhausting gas so that the volume of gas present in said container varies as necessary to acquire zero velocity and neutral buoyancy of the system when a predetermined sea pressure is reached.

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TRYGVE M. BLIX, Primary Examiner