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2
3 METHOD AND APPARATUS FOR REDUCING DRAG IN MARINE VESSELS

4
5 STATEMENT OF GOVERNMENT INTEREST

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

10
11 BACKGROUND OF THE INVENTION

12 (1) Field of the Invention

13 The present invention relates to marine vessels, and more
14 particularly, to a system and method of operation thereof for
15 reducing drag that retards the motion of marine vessels.

16 (2) Description of the Prior Art

17 Marine vessels that move in water experience drag that
18 retards their motion therein. The drag is manifested as a
19 turbulent boundary layer of the fluid that comes into contact
20 with the marine vessel. A number of techniques have been
21 proposed for reducing drag within the turbulent boundary layer.
22 Examples include suction of the boundary layer fluid, injection

1 of fluids into the boundary layer, use of electromagnetic force
2 and other various means. Systems that reduce drag are known and
3 some of which are described in U.S. Patent Nos. 4,991,529;
4 5,117,882; 5,146,863; 5,365,490; 5,575,232; 5,603,278;
5 5,613,456; 5,704,750; and 5,803,409. However, several
6 limitations remain using these approaches with respect to
7 translation of applied technologies to practical applications.
8 It is desired that a system and a method of operation thereof,
9 be provided that reduces drag and finds practical applications
10 to marine vessels.

11 12 SUMMARY OF THE INVENTION

13 Accordingly, it is a general purpose and object of the
14 present invention to provide a system and method of operation
15 thereof, that reduces drag in marine vessels and which is
16 applicable to any situation which requires monitoring and
17 regulation of boundary layered dynamics and applies to all
18 marine vessels. The present invention minimizes the marine
19 vessel drag and thereby maximizes the vessel's fuel consumption
20 efficiency.

21 The system of the present invention comprises an air flow
22 system, a plurality of sensors, and a signal processor that is

1 responsive to application programs. The air flow system is
2 coupled to the boundary layer of the fluid that comes into
3 contact with the marine vessel. The air flow system is
4 responsive for means for varying bubble size interjected into a
5 fluid of the boundary layer and means for varying the flow rate
6 of the fluid interjected into the boundary layer. The means for
7 varying comprises the plurality of sensors, each having an
8 output and interposed in the boundary layer. The sensors detect
9 the flow rate of the boundary layer and the pressure thereof and
10 the information derived from the sensors is used to determine
11 the size of bubbles flowing in the boundary layer. The signal
12 processor receives the output of the sensors and is responsive
13 to the application programs which determine the time rate of
14 change of a chaotic radius (CR) which represents the
15 differential radius (DR) having a range which controls the
16 bubble size and the flow rate injected into the boundary layer.

17

18 BRIEF DESCRIPTION OF THE DRAWINGS

19 A more complete understanding of the invention and many of
20 the attendant advantages thereto will be readily appreciated as
21 the same becomes better understood by reference to the following
22 detailed description when considered in conjunction with the

1 accompanying drawings wherein corresponding reference characters
2 indicate corresponding parts throughout the several views of the
3 drawings and wherein:

4 FIG. 1 is a block diagram of the present invention;

5 FIG. 2 is a schematic showing the interface between the air
6 injection system of FIG. 1 and the boundary layer related to the
7 present invention; and

8 FIG. 3 is a diagrammatic illustration of obtaining the
9 chaotic radius (CR) and differential radius (DR) parameters of
10 the present invention.

11 12 DESCRIPTION OF THE PREFERRED EMBODIMENTS

13 With reference to the drawings, there is shown in FIG. 1 a
14 block diagram of system 10 for reducing the drag to which a
15 marine vessel 12 may be subjected. The marine vessel 12 has its
16 lower surface come into contact with the fluid, such as water,
17 in which it moves and, more importantly, with a boundary layer
18 of the fluid which is a very thin layer of fluid that propagates
19 near the surface of the vessel and has a zero velocity at the
20 surface.

21 The system 10 comprises an air injection system 14 coupled
22 to the boundary layer and has means for varying the bubble size

1 of the fluid injected into the boundary layer along with the
2 flow rate of the fluid injected into the boundary layer. The
3 air injection system 14 injects air through sliding plates 16
4 preferably having perforations 18, and the plates 16 are located
5 along the wall of the hull in which the boundary layer is
6 present. Further, it is preferred that the air injection system
7 be located along the wall of the boundary layer and placed with
8 respect to the stream wise direction of the flow of fluid along
9 the hull.

10 Air flow injection systems used for reducing drag in marine
11 vessels are known and two of such systems are disclosed in the
12 previously mentioned U.S. Patents 5,575,232 ('232) and 5,613,456
13 ('456) both of which are herein incorporated by reference. The
14 air injection system 14 has many of the features of the '456
15 patent and is to be further discussed hereinafter with reference
16 to FIG. 2.

17 The system 10 of FIG. 1, further comprises a plurality of
18 sensors 20 and 22 each having an electrical output and
19 interposed in said boundary layer. The sensor 20 detects the
20 flow rate of the boundary layer, whereas the sensor 22 detects
21 the pressure of the boundary layer. As will be described
22 hereinafter, the information derived from the outputs of sensors

1 20 and 22, sometimes referred to herein as measurement probes,
2 is used to determine the size of bubbles flowing in the boundary
3 layer. The output signals of sensors 20 and 22 are respectively
4 placed on signal paths 24 and 26 both of which are routed to a
5 signal processor 28.

6 Signal processor 28 is responsive to application programs
7 30 which determine the rate of change of a chaotic radius (CR)
8 which represents a differential radius (DR) having a range which
9 controls the bubble size and the flow rate of fluid injected
10 into the boundary layer. The application programs 30, by way of
11 signal processor 28, provides signals on signal paths 32 and 34
12 which are routed to the air injection system 14 that responds to
13 the commands thereon and controls the bubble size and the flow
14 rate interjected into the boundary layer by way of path 36.

15 The system 10, in particular, the application programs 30,
16 utilize novel non-linear signal processing methods, derived from
17 the theories of information and nonlinear oscillations (chaos)
18 to control the turbulent boundary layer of marine vessel 12 for
19 reducing drag. Some of the principles used in the practice of
20 the present invention related to marine vessels are similar to
21 some of the principles disclosed in U.S. Patent 5,730,144

1 related to the efficiency of cardioversion and which is herein
2 incorporated by reference.

3 The non-linear entries used in the practice of the present
4 invention, namely the chaotic radius and differential radius and
5 variants thereof (to be described hereinafter), when operated on
6 the original turbulent boundary layer data obtained from
7 measurement probes 20 and 22 mounted along the hull of a marine
8 vessel 12, provide automatic and precise detection markers for
9 increase or decrease in drag based on a prescribed fluid (i.e.,
10 air) injection and flow rate in the boundary layer. The
11 injected parameter are provided by the air injection system 14
12 in response to the signals applied by signal processing system
13 28 onto signal paths 32 and 34. The advantage of this feature
14 of the present invention is to obtain an optimal mixture of
15 injection (bubble size) and flow rate parameters for minimizing
16 the drag of a marine vessel 12 and thereby maximizing the
17 vessel's fuel consumption efficiency. The air injection system
18 14 may be further described with reference to FIG. 2.

19 FIG. 2 illustrates the air injection system 14, in
20 particular, control line 36 controlling a valve 40 operatively
21 connected to the sliding plate 16 and generating bubbles 42 into
22 a fluid 44 having a boundary layer generally shown as 46. To

1 reduce drag as the liquid 44 flows in a general direction as
2 shown by arrow 48, bubbles 42, especially micro-bubbles, must be
3 positioned within the boundary layer as shown by 46. Bubbles 42
4 are first introduced into the liquid 44 from a gas reservoir
5 within the air injection system 14. The gas is metered out and
6 controlled by the valve 40 in response to the signal on control
7 line 36. The gas in gas reservoir 20 then passes through a
8 porous surface, in particular, the perforations 18 which
9 introduces the bubbles 42 into the liquid 44. In the preferred
10 embodiment, porous surface of the sliding plate 16 is
11 manufactured from sintered metal, as is well known in the art,
12 providing pores of nominal 50 micron approximately minimum size.
13 This allows the bubbles 42 to be of a small size, preferably
14 about 50 microns or more in diameter, which is preferential for
15 drag reduction. The bubbles 42 then flow in a direction
16 generally indicated by arrow 48 along the surface of the vessel
17 12.

18 A primary feature of the present invention is to determine
19 the degree of entropy in the boundary layer 46 for assessing the
20 parameters for reducing the drag of the marine vessel 12. The
21 entropy quantity is used as a means for determining the amount
22 of friction within the boundary layer 46. The entropy parameter

1 is used for similar determinations. For example, a pendulum
2 without friction exhibits perfect oscillatory behavior with zero
3 entropy. A process without friction has no entropy change.
4 With friction there is entropy. A minimum entropy for a given
5 flow rate at the boundary layer 46 defines the optimum condition
6 used by the system 10 for reducing drag.

7 The present invention, in particular, the application
8 programs 30 perform realtime non-linear analysis diagnostics of
9 time series recordings of the boundary layer wall pressures or
10 nearfield velocities. Specifically, as to be further described
11 hereinafter, the application programs 30 calculates the
12 differential radius (DR) such that if a specified level of the
13 DR is reached or exceeded (i.e., high entropy), then an
14 adjustment of the boundary layer control parameters (namely,
15 flow rate and/or bubble size) is accomplished by the air
16 injection system 14. Control parameter adjustments are made
17 based on both historical (default) and realtime data collected
18 from a particular marine vessel and particular sensitivities to
19 DR that may form part of the database of the application
20 programs 30.

21 The DR quantity used by the application program 30 is of
22 particular importance to the present invention. The DR quantity

1 is in itself based on the topological phase space reconstruction
2 of the flow parameter orbit (in this particular case, pressure
3 or velocity respectively provided by the output signals of
4 sensors 22 and 20). The phase space reconstruction is obtained
5 using time series. From a one-dimensional time series (e.g., of
6 the pressure or velocity), a d-dimensional set of vectors is
7 obtained from a sequence of integral time delays of the
8 observations given below by equation (1):

$$9 \quad y(n) = [p(n), p(n+T), p(n+2T), \dots, p(n+(d-1)T)] \quad (1)$$

10 where:

11 $p(n)$ is the original time series datum at time n .

12 $p(n+iT)$ is the datum offset by a delay variable

13 $iT, i=1, 2, \dots, k$.

14 $p(n+(d-1)T)$ is the datum offset by time delay $(d-1)T$.

15 d is the embedding dimension, and

16 n is the index for the time series datum ($n=1, 2, 3 \dots N$)

17 and the number of indices, N , is a selectable quantity.

18 In the practice of the present invention in performing the
19 phase space embedding shown with reference to equation (1), the
20 initial task is to determine values for T and d of equation (1).
21 Moreover, one must ensure the time series of equation (1) has
22 been sampled at a sufficiently high rate such that the time

1 between sample points is shorter than the most significant eddy
2 turn over rates and associate harmonics, sometimes referred to
3 as a small whirlpool, associated with the current of water 44
4 running contrary to the main current of water indicated by
5 directional arrow 48 of FIG. 2 related to the boundary layer 46.

6 The geometric basis for underlying phase space
7 reconstruction, associated with the present invention, is that
8 starting with a 1-dimensional singular variable time series,
9 such as that of equation (1), one is often able to reconstruct
10 the multivariate state space in which the phase-space structure
11 is observed. Practically, one observes in three dimensions
12 although mathematically, in principle, one can compute up to as
13 many dimensions as modern-day computers will reasonably allow.
14 When one views three dimensionally "chaotic attractors" (known
15 in the art) with defined structure, one often observes a
16 distortion of the multivariate structure of a certain higher
17 dimension projected onto a lower (3-dimensional) observation
18 space. Even with the distortion, there remains observable
19 underlying structure, and it is an important consideration in
20 that systems whose computed dimensions are double and triple the
21 observation space in which one views their orbits, show
22 observable features that distinguish them apart.

1 The technique that the present invention, in particular the
2 application programs 30, employs for computing the minimum
3 embedding dimension is based on the feature that when points of
4 higher dimension are projected down to a space of lower
5 dimension, there are overlapping orbits in the low dimensional
6 space. The present invention considers the reverse of this
7 situation. More particularly, as one progresses from low to
8 higher dimensions, one would reasonably expect neighboring
9 points to separate apart. Thus, the technique that the present
10 invention employs is to start with one dimension and
11 successively unfold to higher and higher dimensions, while
12 keeping track of the percentage of nearest neighbors (to be
13 described hereinafter), that spread apart at each integral
14 increase of dimension. The practice of the present invention
15 has added enough additional coordinates when all points near
16 each other are close for dynamical reasons rather than by
17 projection from a higher dimension. One proceeds by determining
18 in dimension "d" which points obtained from the time delays into
19 vectors as above are the nearest neighbors $y_{nn}(n)$ of the point
20 $y(n)$, where $y_{nn}(n)$ is computed using equation (2) given below:

21 $y_{nn}(n) = [v_{nn}(n), \bar{v}_{nn}(n+T), \dots, v_{nn}(n+(d-1)T)]$ (2)

1 The practice of the present invention determines whether or
2 not these points of equation (2) remain close in dimension $(d+1)$
3 where the vector $y(n)$ is augmented by a component $v(n+dT)$ and
4 the quantity $y_{nn}(n)$ is augmented by $v_{nn}(n+dT)$. For small
5 distances the nearest neighbors are true neighbors. For large
6 distances the nearest neighbors are false neighbors which
7 arrived near each other by projection. When the percentage of
8 false neighbors drops to zero, the practice of the present
9 invention has unfolded the chaotic attractor onto a practical
10 dimensional space defined by the minimum embedding dimension of
11 equation (1). The phase space reconstruction is practical in
12 the sense that one optimizes dynamical reconstruction of the
13 signal of interest, such as the pressure or velocity signal on
14 signal paths 26 and 24, respectively, while minimizing computer
15 processing of the signal processor 28.

16 In the practice of the present invention, it has been
17 determined that it is not always necessary to model or process
18 data in the exact dimension of the system 10. Frequently, lower
19 projections are used which can provide equally useful results.
20 For data processing of the turbulent boundary layer pressure or
21 velocity fluctuations, such as related to the present invention,
22 a method for computing the differential radius at successively

1 higher dimensions and complementary to the aforementioned false
2 neighbor unfolding technique, may be employed. The important
3 element of this approach, related to the practice of the present
4 invention, is to seek out a system invariant, that is parameters
5 that do not change with increasing dimension.

6 Non-linear systems, such as those related to boundary
7 layers associated with the present invention, in the parameter
8 regime where the orbits are chaotic are known to generate
9 entropy, which is of importance to the present invention as
10 previously discussed. One quantitative measure of the entropy
11 is the average mutual information (AMI). A second quantitative
12 measure of the entropy is the differential radius (DR).

13 The average mutual information (AMI) quantifies the
14 information theoretic properties of chaotic systems finding
15 application to the present invention, in particular to the
16 application programs 30. The average mutual information (AMI)
17 answers the question: If one collects measurement data in the
18 form of a time series, $p(n)$, such as that of equation (1), where
19 $p(n)=p(t+ndt)$ and where t is the start time, dt is the time
20 between samples, and n is the sample number, then how much
21 information (in bits) does one gather from a measurement at time
22 Tdt later on, namely at time $p(n+T)$. The answer to this

1 question is of particular importance to the signal processor 28
 2 handling the digital quantities of the application programs 30.
 3 The informational theoretic answer to this question requires the
 4 distribution of measurements $p(n)$ and $p(n+T)$ over the set of
 5 measured data and the joint distribution of measurements of
 6 these two quantities, $p(n)$ and $p(n+T)$. The first of these
 7 distributions is $P(p(n))$, the second is $P(p(n+T))$, and the third
 8 is $P(p(n), p(n+T))$. The mutual information between measurements
 9 may be expressed by equation (3) given below:

$$10 \quad \ln [P(p(n), p(n+T)) / P(p(n)) P(p(n+T))] \quad (3)$$

11
 12 where $\ln$ is a natural logarithm. For N observations, the
 13 average over all measurements is the AMI which is a
 14 function of the delay parameter T . Letting $AMI = I(T)$, one
 15 obtains equation (4) given below:

$$16 \quad I(T) = I(T_1) + I(T_2) + \dots + I(T_N) \text{ or } I(T) = \sum I(T_i) \text{ where } i=1, 2, \dots, N \quad (4)$$

17
 18
 19 Alternatively, equation (4) may be expressed as equation
 20 (5) given below:

$$21 \quad I(T_i) = -P(p(i), p(i+T)) \ln [P(p(n), p(n+T)) / (P(p(n)) P(p(n+T)))] \quad (5)$$

1 For equation (5), it should be noted that for
2 independent measurements $p(n)$ and $p(n+T)$, each term in the above
3 sum of equation (5) vanishes due to factorization of the joint
4 probability $P(a,b)=P(a)P(b)$. One would naturally expect two
5 measurements to become independent for very large values of T
6 since chaotic signals rapidly lose memory of earlier entries on
7 their orbits. For the case $T=0$, $I(0)$ is large, indicative of
8 the full knowledge of the measurements. In the general case,
9 $I(T)>0$, and one seeks, in the practice of the present invention,
10 for an intermediate value where $I(T)$ is neither too large or too
11 small. Finding such a value of T determines independent
12 measurements $p(n)$ and $p(n+T)$ in a nonlinear sense. The
13 nonlinear prescription for choosing such a value for T , is to
14 select the first minimum of $I(T)$. This is done in the practice
15 of the present invention by choosing the first zero-crossing of
16 the auto correlation function, often, used in linear analysis
17 and known in the art. In the practice of the present invention,
18 it has been determined that any value of T near the first
19 minimum of $I(T)$ suffices, and oftentimes T is selected as a
20 percentage of the zero crossing of the auto correlation.

21 The second quantitative measurement employed by the present
22 invention for quantification of the entropy, and which is of

1 particular importance to the present invention, is the
2 differential radius (DR), for it is the DR quantity which is
3 preferably used to measure the entropy associated with the
4 boundary layer 46 and hence preferably provides a regulatory
5 mechanism for fluid injection into the boundary layer 46 by
6 means of the air injection system 14. Once an appropriate phase
7 space reconstruction has been obtained using the hereinbefore
8 given descriptions, the DR is derived from a quantity which is
9 herein defined as the chaotic radius (CR) and which may be
10 further described with reference to FIG. 3.

11 FIG. 3 is an illustration related to the chaotic and
12 differential radii parameters of the present invention. More
13 particularly, FIG. 3 illustrates the points yielded from a 1-
14 dimensional time series phase space reconstruction associated
15 with that of equation (1). Typically, FIG. 3 illustrates points
16 50 and 52 respectively associated with the chaotic radius and
17 the differential radius (DR), sometimes referred to as (dr).
18 Point 50 is defined by X quantity 54 having terms $X(t)$ and Y
19 quantity 56 having terms $X(t+p)$. Point 52 is defined by X
20 quantity 58 having terms $X(t+d)$ and Y quantity 60 having terms
21 $X(t+d+p)$. The terms d and p respectively represent the smallest

1 time sample associated with gathering the data of FIG. 3 and a
2 delay period for gathering the data of FIG. 3.

3 Further, FIG. 3 illustrates vectors quantities $r(62)$,
4 $w(64)$, $dr(66)$, and $dw(68)$. The definition for the vector
5 quantities shown in FIG. 3 are given in Table 1. It should be
6 noted that the basis for detecting chaotic dynamics in a
7 turbulent boundary layer upon which both the chaotic radius (CR)
8 and the differential radius (DR) are predicated was first
9 described in my U.S. Patent No. 5,365,490 entitled: "Method And
10 System For Reducing Drag On A Body Moving Through A Fluid
11 Medium." This U.S. Patent is incorporated by reference in
12 subject patent application.

13
14 TABLE 1

15 CHAOTIC RADIUS (r) AND CHAOTIC FREQUENCY (w) (2-D):

16 $r = [X(t)^2 + X(t+p)^2]^{1/2}$

17 $w = \arctan [X(t+p) / X(t)]$

18
19 DIFFERENTIAL RADIUS (dr) AND DIFFERENTIAL FREQUENCY (dw) (2-D):

20 $dr = [[X(t+d) - X(t)]^2 + [X(t+d+p) - X(t+p)]^2]^{1/2}$

21 $dw = \arctan [[X(t+d+p) - X(t+p)] / [X(t+d) - X(t)]]$

1 Variant of DIFFERENTIAL RADIUS (dr) (2-D):

2 $dr = r(i+1) - r(i),$ i is time index

3 From FIG. 3, and Table 1, it is seen that the chaotic
4 radius (r), sometimes referred to as CR, is obtained by drawing
5 a line (62) from a given point (50) in the phase space to a
6 known reference point, such as the origin (O shown in FIG. 3)
7 which is typically selected as a point of reference. It should
8 be noted that for a phase space having a 2- or 3- dimensions in
9 the usual Euclidean sense, or the line to the origin may be a
10 hyper-line if the extension is based on a four or higher
11 dimensional phase space reconstruction. FIG. 3 represents a 2-
12 dimensional (2-D) illustration.

13 For the case illustrated in FIG. 3, the chaotic radius (r)
14 is computed as a hypotenuse of a right triangle in the sense of
15 Euclidean. The chaotic radius (r) for higher dimensions (i.e.,
16 hyper-triangles) are computed by extension of the sum of squared
17 variables in the brackets for the formula for chaotic radius (r)
18 shown in Table 1. The quantity differential radius (dr) is
19 computed simply as the time of change of the chaotic radius (r)
20 quantity. It should be noted that the differential radius (dr)
21 quantity is a natural measurement of the changing state of a
22 dynamical system. As previously mentioned, for example, a

1 pendulum without friction exhibits perfect oscillatory behavior
2 with zero entropy. In the present invention, the chaotic radius
3 (r) is a constant and the differential radius (dr) is zero for
4 such zero entropy. If the system is violently disturbed, the
5 differential radius (dr) quantity will rise in proportion to the
6 increase in entropy due to disruptive forces of the system. It
7 is the differential radius (dr) quantity that is used by the
8 present invention to ascertain the amount of disruption of the
9 otherwise laminar fluid motion in the boundary layer 46 that
10 allows the present invention to regulate and control the drag
11 within the boundary layer.

12 For example, in the practice of the present invention it
13 has been determined that if the differential radius (dr) exceeds
14 a prescribed threshold level, then bubble size and flow rate
15 adjustments are made until the dr is reduced below the
16 prescribed threshold level, so as to reduce the turbulence in
17 the boundary layer 46 and, thus, the drag.

18 It is now appreciated that the practice of the present
19 invention provides for non-linear signal processing methods
20 utilizing non-linear oscillations (chaos) used to determine
21 turbulent boundary layers that are then controlled for reducing
22 drag. The present invention by determining the bubble size and

1 the flow parameters for minimizing the marine vessels drag
2 maximizes the vessels fuel consumption efficiency.

3 Although the present invention has been described for drag
4 reduction of marine vessels, it should be appreciated that the
5 practice of the present invention applies to any situation
6 requiring moderating and regulation of boundary layer dynamics
7 and applies to all marine vessels.

8 It will be understood that various changes in the details,
9 steps and arrangements of parts, which have been herein
10 described and illustrated in order to explain the nature of the
11 invention, may be made by those skilled in the art within the
12 principle and scope of the invention.

13

2
3 METHOD AND APPARATUS FOR REDUCING DRAG IN MARINE VESSELS

4
5 ABSTRACT OF THE DISCLOSURE

6 A system is disclosed that applies non-linear signal
7 processing methods derived from theories of information and non-
8 linear oscillations (chaos) to control the turbulent boundary
9 layer of marine vessels in order to reduce the drag to which the
10 vessels encountered while moving in water. The system uses
11 measurement probes mounted along the hull of a marine vessel to
12 provide detection markers for increase or decrease in the drag
13 based on a prescribed fluid (i.e., air) injection and flow rate
14 in boundary layer. The invention utilizes a differential radius
15 (DR) to determine the minimum entropy for a given flow rate in
16 the boundary layer which defines the optimum condition used by
17 the system for reducing drag.

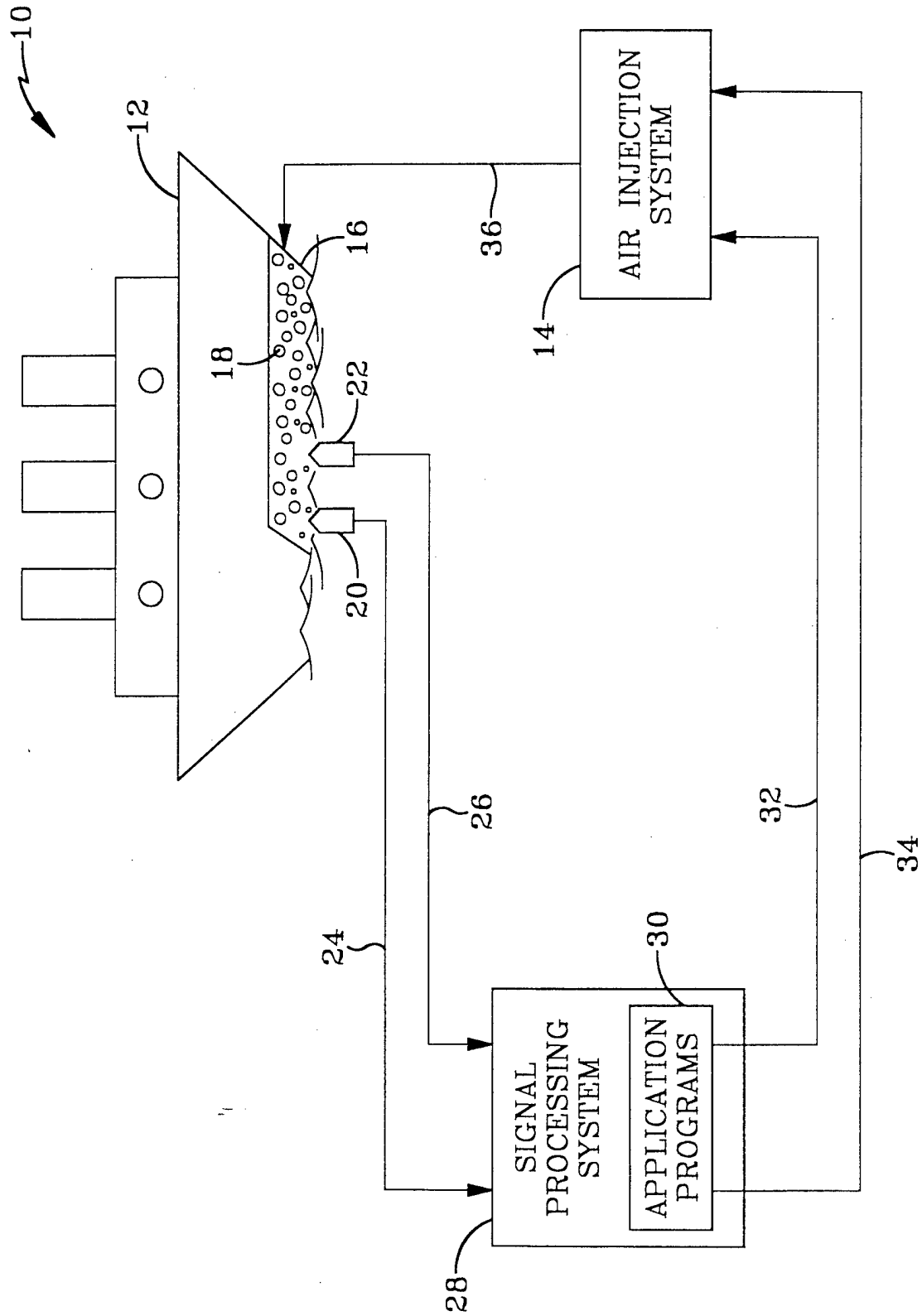


FIG-1

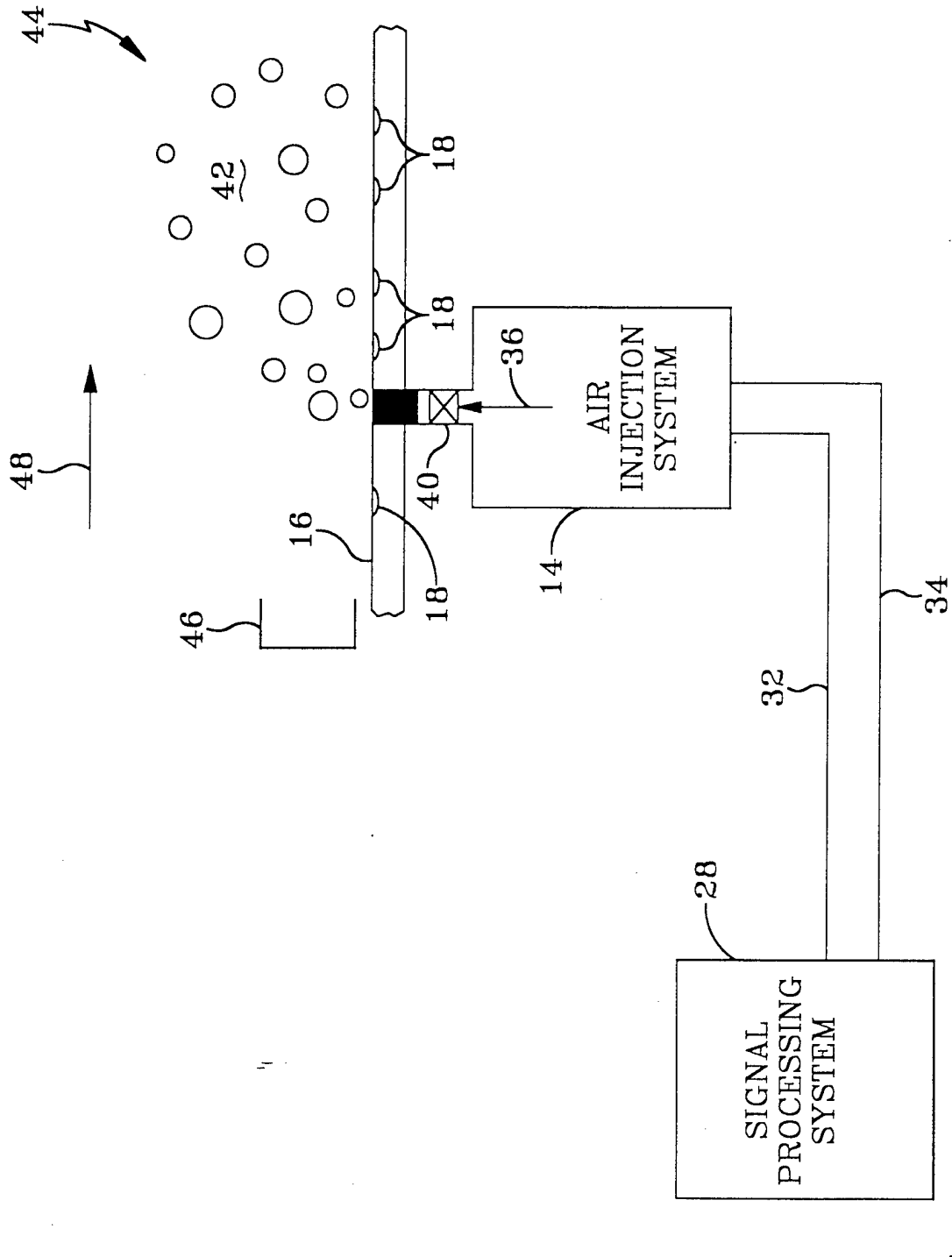


FIG-2

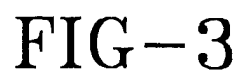


FIG-3