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METHOD AND APPARATUS FOR REDUCING DRAG IN MARINE VESSELS

STATEMENT OF 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

(1) Field of the Invention

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

(2) Description of the Prior Art

Marine vessels that move in water experience drag that retards their motion therein. The drag is manifested as a turbulent boundary layer of the fluid that comes into contact with the marine vessel. A number of techniques have been proposed for reducing drag within the turbulent boundary layer. Examples include suction of the boundary layer fluid, injection
of fluids into the boundary layer, use of electromagnetic force and other various means. Systems that reduce drag are known and some of which are described in U.S. Patent Nos. 4,991,529; 5,117,882; 5,146,863; 5,365,490; 5,575,232; 5,603,278; 5,613,456; 5,704,750; and 5,803,409. However, several limitations remain using these approaches with respect to translation of applied technologies to practical applications. It is desired that a system and a method of operation thereof, be provided that reduces drag and finds practical applications to marine vessels.

SUMMARY OF THE INVENTION

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

The system of the present invention comprises an air flow system, a plurality of sensors, and a signal processor that is
responsive to application programs. The air flow system is
coupled to the boundary layer of the fluid that comes into
contact with the marine vessel. The air flow system is
responsive for means for varying bubble size interjected into a
fluid of the boundary layer and means for varying the flow rate
of the fluid interjected into the boundary layer. The means for
varying comprises the plurality of sensors, each having an
output and interposed in the boundary layer. The sensors detect
the flow rate of the boundary layer and the pressure thereof and
the information derived from the sensors is used to determine
the size of bubbles flowing in the boundary layer. The signal
processor receives the output of the sensors and is responsive
to the application programs which determine the time rate of
change of a chaotic radius (CR) which represents the
differential radius (DR) having a range which controls the
bubble size and the flow rate injected into the boundary layer.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the invention and many of
the attendant advantages thereto will be readily appreciated as
the same becomes better understood by reference to the following
detailed description when considered in conjunction with the
accompanying drawings wherein corresponding reference characters indicate corresponding parts throughout the several views of the drawings and wherein:

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

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

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

DESCRIPTION OF THE PREFERRED EMBODIMENTS

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

The system 10 comprises an air injection system 14 coupled to the boundary layer and has means for varying the bubble size
of the fluid injected into the boundary layer along with the
flow rate of the fluid injected into the boundary layer. The
air injection system 14 injects air through sliding plates 16
preferably having perforations 18, and the plates 16 are located
along the wall of the hull in which the boundary layer is
present. Further, it is preferred that the air injection system
be located along the wall of the boundary layer and placed with
respect to the stream wise direction of the flow of fluid along
the hull.

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

The system 10 of FIG. 1, further comprises a plurality of
sensors 20 and 22 each having an electrical output and
interposed in said boundary layer. The sensor 20 detects the
flow rate of the boundary layer, whereas the sensor 22 detects
the pressure of the boundary layer. As will be described
hereinafter, the information derived from the outputs of sensors
20 and 22, sometimes referred to herein as measurement probes, is used to determine the size of bubbles flowing in the boundary layer. The output signals of sensors 20 and 22 are respectively placed on signal paths 24 and 26 both of which are routed to a signal processor 28.

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

The system 10, in particular, the application programs 30, utilize novel non-linear signal processing methods, derived from the theories of information and nonlinear oscillations (chaos) to control the turbulent boundary layer of marine vessel 12 for reducing drag. Some of the principles used in the practice of the present invention related to marine vessels are similar to some of the principles disclosed in U.S. Patent 5,730,144
related to the efficiency of cardioversion and which is herein
incorporated by reference.

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

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

A primary feature of the present invention is to determine the degree of entropy in the boundary layer 46 for assessing the parameters for reducing the drag of the marine vessel 12. The entropy quantity is used as a means for determining the amount of friction within the boundary layer 46. The entropy parameter
is used for similar determinations. For example, a pendulum
without friction exhibits perfect oscillatory behavior with zero
entropy. A process without friction has no entropy change.
With friction there is entropy. A minimum entropy for a given
flow rate at the boundary layer 46 defines the optimum condition
used by the system 10 for reducing drag.

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

The DR quantity used by the application program 30 is of
particular importance to the present invention. The DR quantity
is in itself based on the topological phase space reconstruction of the flow parameter orbit (in this particular case, pressure or velocity respectively provided by the output signals of sensors 22 and 20). The phase space reconstruction is obtained using time series. From a one-dimensional time series (e.g., of the pressure or velocity), a d-dimensional set of vectors is obtained from a sequence of integral time delays of the observations given below by equation (1):

\[ y(n) = [p(n), p(n+T), p(n+2T), \ldots, p(n+(d-1)T)] \]  

where:

- \( p(n) \) is the original time series datum at time \( n \).
- \( p(n+iT) \) is the datum offset by a delay variable \( iT, i=1,2,\ldots,k \).
- \( p(n+(d-1)T) \) is the datum offset by time delay \( (d-1)T \).
- \( d \) is the embedding dimension, and
- \( n \) is the index for the time series datum \( (n=1,2,3\ldots,N) \) and the number of indices, \( N \), is a selectable quantity.

In the practice of the present invention in performing the phase space embedding shown with reference to equation (1), the initial task is to determine values for \( T \) and \( d \) of equation (1). Moreover, one must ensure the time series of equation (1) has been sampled at a sufficiently high rate such that the time
between sample points is shorter than the most significant eddy
turn over rates and associate harmonics, sometimes referred to
as a small whirlpool, associated with the current of water running contrary to the main current of water indicated by
directional arrow 48 of FIG. 2 related to the boundary layer.

The geometric basis for underlying phase space
reconstruction, associated with the present invention, is that
starting with a 1-dimensional singular variable time series,
such as that of equation (1), one is often able to reconstruct
the multivariate state space in which the phase-space structure
is observed. Practically, one observes in three dimensions
although mathematically, in principle, one can compute up to as
many dimensions as modern-day computers will reasonably allow.

When one views three dimensionally "chaotic attractors" (known
in the art) with defined structure, one often observes a
distortion of the multivariate structure of a certain higher
dimension projected onto a lower (3-dimensional) observation
space. Even with the distortion, there remains observable
underlying structure, and it is an important consideration in
that systems whose computed dimensions are double and triple the
observation space in which one views their orbits, show
observable features that distinguish them apart.
The technique that the present invention, in particular the
application programs 30, employs for computing the minimum
embedding dimension is based on the feature that when points of
higher dimension are projected down to a space of lower
dimension, there are overlapping orbits in the low dimensional
space. The present invention considers the reverse of this
situation. More particularly, as one progresses from low to
higher dimensions, one would reasonably expect neighboring
points to separate apart. Thus, the technique that the present
invention employs is to start with one dimension and
successively unfold to higher and higher dimensions, while
keeping track of the percentage of nearest neighbors (to be
described hereinafter), that spread apart at each integral
increase of dimension. The practice of the present invention
has added enough additional coordinates when all points near
each other are close for dynamical reasons rather than by
projection from a higher dimension. One proceeds by determining
in dimension "d" which points obtained from the time delays into
vectors as above are the nearest neighbors $y_{nn}(n)$ of the point
$y(n)$, where $y_{nn}(n)$ is computed using equation (2) given below:

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

In the practice of the present invention, it has been determined that it is not always necessary to model or process data in the exact dimension of the system 10. Frequently, lower projections are used which can provide equally useful results. For data processing of the turbulent boundary layer pressure or velocity fluctuations, such as related to the present invention, a method for computing the differential radius at successively
higher dimensions and complementary to the aforementioned false
neighbor unfolding technique, may be employed. The important
element of this approach, related to the practice of the present
invention, is to seek out a system invariant, that is parameters
that do not change with increasing dimension.

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

The average mutual information (AMI) quantifies the
information theoretic properties of chaotic systems finding
application to the present invention, in particular to the
application programs 30. The average mutual information (AMI)
answers the question: If one collects measurement data in the
form of a time series, p(n), such as that of equation (1), where
p(n)=p(t+ndt) and where t is the start time, dt is the time
between samples, and n is the sample number, then how much
information (in bits) does one gather from a measurement at time
Tdt later on, namely at time p(n+T). The answer to this
question is of particular importance to the signal processor handling the digital quantities of the application programs. The informational theoretic answer to this question requires the distribution of measurements \( p(n) \) and \( p(n+T) \) over the set of measured data and the joint distribution of measurements of these two quantities, \( p(n) \) and \( p(n+T) \). The first of these distributions is \( P(p(n)) \), the second is \( P(p(n+T)) \), and the third is \( P(p(n), p(n+T)) \). The mutual information between measurements may be expressed by equation (3) given below:

\[
\ln \left( \frac{P(p(n), p(n+T))}{P(p(n+T))} \right)
\]

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

\[
I(T) = I(T_1) + I(T_2) + \ldots + I(T_N) \text{ or } I(T) = (T_i) \quad \text{where } i=1,2,\ldots,N
\]

Alternatively, equation (4) may be expressed as equation (5) given below:

\[
I(T_i) = P(p(i), p(i+T)) \star \ln \left( \frac{P(p(n), p(n+T))}{P(p(n))P(p(n+T))} \right)
\]
For equation (5), it should be noted that for independent measurements \( p(n) \) and \( p(n+T) \), each term in the above sum of equation (5) vanishes due to factorization of the joint probability \( P(a,b) = P(a)P(b) \). One would naturally expect two measurements to become independent for very large values of \( T \) since chaotic signals rapidly lose memory of earlier entries on their orbits. For the case \( T=0 \), \( I(0) \) is large, indicative of the full knowledge of the measurements. In the general case, \( I(T) > 0 \), and one seeks, in the practice of the present invention, for an intermediate value where \( I(T) \) is neither too large or too small. Finding such a value of \( T \) determines independent measurements \( p(n) \) and \( p(n+T) \) in a nonlinear sense. The nonlinear prescription for choosing such a value for \( T \), is to select the first minimum of \( I(T) \). This is done in the practice of the present invention by choosing the first zero-crossing of the auto correlation function, often, used in linear analysis and known in the art. In the practice of the present invention, it has been determined that any value of \( T \) near the first minimum of \( I(T) \) suffices, and oftentimes \( T \) is selected as a percentage of the zero crossing of the auto correlation.

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

FIG. 3 is an illustration related to the chaotic and 
differential radii parameters of the present invention. More 
particularly, FIG. 3 illustrates the points yielded from a 1-
dimensional time series phase space reconstruction associated 
with that of equation (1). Typically, FIG. 3 illustrates points 
50 and 52 respectively associated with the chaotic radius and 
the differential radius (DR), sometimes referred to as (dr).

Point 50 is defined by X quantity 54 having terms X(t) and Y 
quantity 56 having terms X(t+p). Point 52 is defined by X 
quantity 58 having terms X(t+d) and Y quantity 60 having terms 
X(t+d+p). The terms d and p respectively represent the smallest
time sample associated with gathering the data of FIG. 3 and a
delay period for gathering the data of FIG. 3.

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

<table>
<thead>
<tr>
<th>TABLE 1</th>
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<tr>
<td>CHAOTIC RADIUS ((r)) AND CHAOTIC FREQUENCY ((w)) (2-D):</td>
</tr>
<tr>
<td>( r = [X(t)^2 + X(t+p)^2]^{\frac{1}{2}} )</td>
</tr>
<tr>
<td>( w = \arctan \left( \frac{X(t+p)}{X(t)} \right) )</td>
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| DIFFERENTIAL RADIUS \((dr)\) AND DIFFERENTIAL FREQUENCY \((dw)\) (2-D): |
| \( dr = [\left( X(t+d) - X(t) \right)^2 + \left( X(t+d+p) - X(t+p) \right)^2]^{\frac{1}{2}} \) |
| \( dw = \arctan \left( \frac{X(t+d+p) - X(t+p)}{X(t+d) - X(t)} \right) \) |
Variant of DIFFERENTIAL RADIUS (dr) (2-D):

\[ dr = r(i+1) - r(i), \quad i \text{ is time index} \]

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

For the case illustrated in FIG. 3, the chaotic radius (r) is computed as a hypotenuse of a right triangle in the sense of Euclidean. The chaotic radius (r) for higher dimensions (i.e., hyper-triangles) are computed by extension of the sum of squared variables in the brackets for the formula for chaotic radius (r) shown in Table 1. The quantity differential radius (dr) is computed simply as the time of change of the chaotic radius (r) quantity. It should be noted that the differential radius (dr) quantity is a natural measurement of the changing state of a dynamical system. As previously mentioned, for example, a
pendulum without friction exhibits perfect oscillatory behavior with zero entropy. In the present invention, the chaotic radius \((r)\) is a constant and the differential radius \((dr)\) is zero for such zero entropy. If the system is violently disturbed, the differential radius \((dr)\) quantity will rise in proportion to the increase in entropy due to disruptive forces of the system. It is the differential radius \((dr)\) quantity that is used by the present invention to ascertain the amount of disruption of the otherwise laminar fluid motion in the boundary layer 46 that allows the present invention to regulate and control the drag within the boundary layer.

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

It is now appreciated that the practice of the present invention provides for non-linear signal processing methods utilizing non-linear oscillations (chaos) used to determine turbulent boundary layers that are then controlled for reducing drag. The present invention by determining the bubble size and
the flow parameters for minimizing the marine vessels drag
maximizes the vessels fuel consumption efficiency.

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

It will be understood that various changes in the details,
steps and arrangements of parts, which have been herein
described and illustrated in order to explain the nature of the
invention, may be made by those skilled in the art within the
principle and scope of the invention.
METHOD AND APPARATUS FOR REDUCING DRAG IN MARINE VESSELS

ABSTRACT OF THE DISCLOSURE

A system is disclosed that applies non-linear signal processing methods derived from theories of information and non-linear oscillations (chaos) to control the turbulent boundary layer of marine vessels in order to reduce the drag to which the vessels encountered while moving in water. The system uses measurement probes mounted along the hull of a marine vessel to provide detection markers for increase or decrease in the drag based on a prescribed fluid (i.e., air) injection and flow rate in boundary layer. The invention utilizes a differential radius (DR) to determine the minimum entropy for a given flow rate in the boundary layer which defines the optimum condition used by the system for reducing drag.
FIG-3

DIFFERENTIAL RADIUS (DR)

CHAOTIC RADIUS (CR)