



DEPARTMENT OF THE NAVY
NAVAL UNDERSEA WARFARE CENTER
DIVISION NEWPORT
OFFICE OF COUNSEL (PATENTS)
1176 HOWELL STREET
BUILDING 112T, CODE 000C
NEWPORT, RHODE ISLAND 02841-1708

PHONE: 401 832-4736
DSN: 432-4736

FAX: 401 832-1231
DSN: 432-1231



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PATENT COUNSEL
NAVAL UNDERSEA WARFARE CENTER
1176 HOWELL ST.
CODE 000C, BLDG. 112T
NEWPORT, RI 02841

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Inventor Stephen A. Huyer

If you have any questions please contact James M. Kasischke, Supervisory Patent Counsel, at 401-832-4230.

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3 A METHOD TO SIMULATE UNSTEADY TURBULENT
4 FLOWS USING A VORTICITY BASED METHOD

6 STATEMENT OF GOVERNMENT INTEREST

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

12 BACKGROUND OF THE INVENTION

13 1. Field of the Invention

14 The present invention generally relates to a method for
15 simulating turbulent fluid flows. More particularly the
16 invention relates to a method for simulating turbulent fluid
17 flows that captures the mean quantities of the flow field but
18 does not filter out the high wavenumber components.

19 2. Description of the Prior Art

20 The ability to numerically simulate turbulent flows has been
21 somewhat elusive. This problem is relevant to a variety Navy
22 applications dealing with unsteady hydrodynamics. For example,
23 turbulence produced in the boundary layer on a body is ingested
24 into a propulsor resulting in a dynamic unsteady response by the
25 individual blades. Unsteady turbulent wakes produced by undersea

1 vehicles can be used to characterize the body that initially
2 produced it. Turbulent flows are produced by any vehicle
3 traveling in a fluid and result due to vorticity generated at the
4 body surface. By properly simulating these flows in space and
5 time, one can develop advanced computational models of propulsor
6 unsteady forces or assist in the development of wake tracking
7 algorithms.

8 There have been several efforts to simulate the formation of
9 wakes and turbulent boundary layers. Most of these methods
10 employ solution of the Navier-Stokes equations on a structured
11 grid. Turbulent effects are then modeled using some type of
12 turbulence model. For example, to model unsteady wakes, a method
13 has been developed that solves the Reynolds Averaged Navier-
14 Stokes (RANS) equations on a fixed grid. It utilizes a k-e
15 turbulence model and obtains the closure coefficients via
16 experimental data. It has been used successfully to predict the
17 time mean flow values and turbulence levels given an initial flow
18 formed by some vehicle geometry. This solution of the unsteady
19 flow is quite adequate if mean values are desired. It
20 effectively provides an ensemble average over many realizations.
21 If more realistic, single realizations of the wake are desired,
22 however, the above solution will be inadequate.

23 With this in mind, an improved technique was developed to
24 effectively construct single realizations of the wake. To
25 accomplish this, the improved technique represents the flow as a

1 truncated Fourier series. Statistical information provided from
2 experiments is used to transform the normal velocity distribution
3 into a log-normal distribution with appropriate mean and
4 variance. An algorithm was then developed to generate single
5 realizations of the wake.

6 The Fourier series method works well in a statistical sense,
7 but there is no way to ensure that the flow is spatially
8 correlated since no phase information of the computations is
9 available. Efforts to model the flow structure of turbulent
10 boundary layers suffer from the same complications. Indeed, most
11 of the research conducted to model the turbulent boundary layer
12 is focused on achieving agreement with mean values. The unsteady
13 vortical flows are often considered too complex to resolve.
14 Large eddy simulations (LES) attempt to better model the higher
15 wavenumber structure of the flow, but they too are solved on a
16 structured grid and do not explicitly compute the flow vorticity.

17 Physically, turbulent boundary layers and wakes are composed
18 of numerous vortex structures. Over time, these structures are
19 advected by the local flow and the evolution of the vorticity
20 field governs the development of the entire flow field. Since
21 the flow is composed of these structures, flow properties
22 including local velocity and vorticity will be correlated in both
23 space and time. Grid based methodologies are unable to account
24 for this since the turbulent flow properties are only satisfied
25 statistically and are effectively ensemble averaged (for RANS) or

1 eliminate high wavenumber behavior (LES). This makes it
2 difficult to generate true single realizations of the flow.

3 Since turbulent boundary layers and wakes are composed of
4 the shed vorticity from the body that generated them, a vorticity
5 based method offers an alternative to the traditional
6 computational approaches (e.g., RANS or spectral methods).
7 Vortex blob methods are known in the art. In these blob methods,
8 the vorticity field is modeled on a set of spherical vortex
9 elements with a prescribed core radius and element overlap to
10 ensure a continuous vorticity field. The vorticity amplitude
11 (the volume integral of vorticity) determines the strength of the
12 blob. A collocation blob method is used to determine the
13 vorticity on a set of points. The vorticity is then evolved
14 according to the vorticity equation.

15 Recent efforts utilizing vortex filaments to model turbulent
16 boundary layer flow structure are also known in the art. Vortex
17 filaments are constructed from the top layer of vortex sheets
18 representing a surface and then are advected by the flow as
19 material elements. In the outer region, the Euler equations are
20 used to evolve the vorticity of the filaments and viscous
21 diffusion is assumed to be small. The difficulty with some of
22 the mathematical models is that the models are only applicable
23 for small aspect ratio filaments whose ratio of length to core
24 radius is on the order of one. The prior art teaches full
25 mathematical expressions for filaments of a defined core radius.

1 There are other potential methods that can be used to model
2 the turbulent flow; however, it is desirable to find a method
3 that captures the mean quantities of the flow field but does not
4 inherently filter out the high wavenumber components.

5

6

SUMMARY OF THE INVENTION

7

8 In view of these requirements, the current invention
9 provides a computerized method for determining the velocity field
10 of a three-dimensional fluid flow over a submerged body. Inflow
11 velocities, turbulence, spectral behavior is provided over a body
12 geometry. The method uses filament elements near the body and
13 blob elements at a distance from the body. Velocity and
14 vorticity are calculated at each time increment and then the
15 elements are evolved based on the calculated values. Blob
16 elements are moved using the centroid of the blob, and filament
17 elements are moved by use the ends of the filaments. New
18 elements are added as required upstream in the flow field. The
19 time is incremented and the routine is repeated for a period of
20 interest, providing a model of the flow field about the body.
21 Hairpin filaments can be modeled by attaching multiple filaments
22 end to end.

22

23

BRIEF DESCRIPTION OF THE DRAWINGS

24

25

The figures are for illustration purposes only and are not
drawn to scale. The invention itself, however, both as to

1 organization and method of operation, may best be understood by
2 reference to the detailed description which follows taken in
3 conjunction with the accompanying drawings in which:

4 FIG. 1 is a diagram showing the basic coordinates on a blob
5 element;

6 FIG. 2 is a diagram showing coordinates on a filament
7 element;

8 FIG. 3 is a flowchart showing the method for simulating a
9 flow according to the current invention;

10 FIG. 4A is a three-dimensional diagram showing the
11 development of a vortex loop as it moves downstream;

12 FIG. 4B is a two-dimensional diagram showing the
13 relationship of a vortex loop at various time intervals about an
14 underwater vehicle; and

15 FIG. 5 is a diagram showing vector elements around an
16 underwater vehicle as modeled by this method.

17

18 DESCRIPTION OF THE PREFERRED EMBODIMENT

19 In describing the preferred embodiments of the present
20 invention, reference will be made herein to FIGS. 1-3 of the
21 drawings in which like numerals refer to like features of the
22 invention.

23 The current method utilizes vortex filaments to model
24 boundary layer structures in order to provide a low wavenumber
25 component to the flow. A random distribution of vortex blobs is

1 then used to model the higher wavenumber components. Vortex
2 filaments are used to model the shed vorticity from wakes created
3 by normal structures and are oriented in such a manner as to
4 provide the measured velocity defect. A boundary element
5 calculation of the hull is used to model the hull near wall
6 vorticity. Finally, since the normal structures produce lift
7 (and hence a swirl component), a vortex lattice is used to model
8 the mean near wall vorticity and wake vorticity due to this
9 effect. This is treated separately from the shed boundary layer
10 vorticity for the normal structures. Results of the model are
11 then compared with experimental data as stated above.

12 In order to properly model the turbulent inflow, the
13 computational models must reproduce the proper turbulent
14 intensity and spectra. Turbulent boundary layers are largely
15 composed of hairpin vortical structures that are advected as
16 material elements. These vortical structures are known to be
17 oriented in the boundary layer in a semi-organized manner. This
18 makes this turbulent inflow model amenable to vorticity based
19 models.

20 This disclosure implements vortex blob and filament methods
21 into a vorticity based solution methodology that is described in
22 United States Patent No. 6,424,923 by Huyer and Grant and is
23 incorporated by reference herein. FIG. 1 shows a representation
24 of a blob element 10. Blobs are defined by a characteristic
25 radius, R , and vorticity amplitude, Ω . The centroid 12 of the

1 blob 10 is used for localizing the blob. FIG. 2 shows a
 2 representation of a filament element 14. Filament element 14 has
 3 end points 1 and 2. Core 16 is shown by cylinder surface.
 4 Filaments are characterized by a core radius, σ , length, $\Delta\ell$, and
 5 circulation vector, $\vec{\Omega}$. $\hat{\Omega}$ is the circulation unit vector which
 6 is along the axis of the filament element 14. A local coordinate
 7 system having a radial axis r and an axial axis z is further
 8 applied to the filament element 14. "i" is the origin of the
 9 filament 14. "j" is a field point for finding the velocity.
 10 "r₁" and "r₂" are the radial distances to the end points 1 and 2
 11 of the filament element 14. \vec{r}_{ij} is the vector from the origin i
 12 to point of interest j. "r_{ij}" is the magnitude of radial
 13 coordinate to the centerline. In this version, vortex blobs and
 14 vortex filaments are used to model unsteady wake flows.
 15 Expressions for the velocity and vorticity fields due to vortex
 16 blobs are given by:

$$\begin{aligned}
 &17 \\
 &18 \quad \vec{u}(\vec{x}, t) = \vec{v}(\vec{x}, t) + \frac{P\left(3/2, |\vec{x} - \vec{x}_n|^2 / R_n^2\right)}{4\pi|\vec{x} - \vec{x}_n|^3} \Omega_n \times (\vec{x} - \vec{x}_n) \quad (1) \\
 &19
 \end{aligned}$$

20 P(a, z) is the incomplete gamma function with limits P = 0 at z =
 21 0 and P = 1 as z → ∞. For a = 3/2 and z = x², where x is real,
 22 P(a, z) is given in terms of the error function:

$$\begin{aligned}
 &23 \quad P(3/2, x^2) = \text{erf}(x) - \frac{2xe^{-x^2}}{\pi^{1/2}} \quad (2)
 \end{aligned}$$

1 The expression for the vorticity is:

2

$$3 \quad \bar{\omega}(\bar{x}, t) = \sum_{n=1}^N \left\{ \frac{\Omega_n}{\pi^{3/2} R_n^3} \exp(-|\bar{x} - \bar{x}_n|^2 / R_n^2) - \nabla \left[\frac{P(3/2, |\bar{x} - \bar{x}_n|^2 / R_n^2)}{4\pi |\bar{x} - \bar{x}_n|^3} \Omega_n \times (\bar{x} - \bar{x}_n) \right] \right\} \quad (3)$$

4

5 The vorticity in (3) is divergence free. If the vorticity is

6 known at the control points, a matrix equation needs to be

7 developed to solve for the element amplitudes. (3) can be

8 written:

9

$$10 \quad \bar{\omega}(\bar{x}, t) = \sum_{n=1}^N \left\{ W_{mn} \Omega_n - A_{mn} \frac{\bar{x}_m - \bar{x}_n}{|\bar{x}_m - \bar{x}_n|^2} [\Omega_n \cdot (\bar{x}_m - \bar{x}_n)] \right\} \quad (4)$$

11

12 The index m refers to the control point locations, and W_{mn} and A_{mn}

13 are $N \times N$ time dependent matrices defined by:

$$14 \quad W_{mn} = \frac{1}{\pi^{3/2} R_n^3} \exp\left(\frac{-|\bar{x}_m - \bar{x}_n|^2}{R_n^2}\right) - \frac{1}{4\pi |\bar{x}_m - \bar{x}_n|^3} P\left(3/2, |\bar{x}_m - \bar{x}_n|^2 / R_n^2\right) \quad (5)$$
$$15 \quad A_{mn} = \frac{1}{\pi^{3/2} R_n^3} \exp\left(\frac{-|\bar{x}_m - \bar{x}_n|^2}{R_n^2}\right) - \frac{3}{4\pi |\bar{x}_m - \bar{x}_n|^3} P\left(3/2, |\bar{x}_m - \bar{x}_n|^2 / R_n^2\right)$$

15

16 The induced velocity due to a vortex filament with core

17 radius, σ , length, $\delta \ell$, circulation, Ω , and circulation unit

18 vector, $\hat{\Omega}$, is shown in the prior art. It is based on the

1 geometry shown in FIG. 2 and applies to the velocity field
 2 outside the core:

$$3 \quad \bar{u}(\bar{x}, t) = -\frac{\Omega}{4\pi} \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \left(\frac{1}{r_1 + r_2 - \delta\ell} - \frac{1}{r_1 + r_2 + \delta\ell} \right) \cdot \hat{\Omega} \times \bar{r}_{ij} \quad (6)$$

4
 5 Due to the singularity in the core, the prior art defines another
 6 expression for the velocity in the core. Unfortunately, this
 7 produces a discontinuity in the velocity distribution. This may
 8 be remedied by defining a smoothing function. It was found that
 9 for this particular velocity expression, an appropriate smoothing
 10 function is:

$$12 \quad \phi(r/\sigma) = 1 - \left(1 - 1.5 \left(\frac{r_{ij}}{\sigma} \right)^{2.5} \right) e^{-(r_{ij}/\sigma)^{2.5}} \quad (7)$$

13
 14 The full velocity field then becomes by multiplying (6) by (7):

$$16 \quad \bar{u}(\bar{x}, t) = -\frac{\Omega}{4\pi} \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \left(\frac{1}{r_1 + r_2 - \delta\ell} - \frac{1}{r_1 + r_2 + \delta\ell} \right) \cdot \hat{\Omega} \times \bar{r}_{ij} \cdot \phi(r/\sigma_n) \quad (8)$$

17
 18 The vorticity along the filament can easily be derived by
 19 taking the curl of (8). In the local system, the vorticity is
 20 non-zero along z and along r . Define:

21

$$\begin{aligned}
\alpha(r, z) &= \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \left(\frac{1}{r_1 + r_2 - \delta\ell} - \frac{1}{r_1 + r_2 + \delta\ell} \right) \\
\frac{\partial\alpha(r, z)}{\partial r} &= -r \left[\left(\frac{1}{r_1^3} + \frac{1}{r_2^3} \right) \left(\frac{1}{r_1 + r_2 - \delta\ell} - \frac{1}{r_1 + r_2 + \delta\ell} \right) \right. \\
&\quad \left. + \left(\frac{1}{r_1} + \frac{1}{r_2} \right)^2 \left(\frac{1}{(r_1 + r_2 - \delta\ell)^2} - \frac{1}{(r_1 + r_2 + \delta\ell)^2} \right) \right] \\
\frac{\partial\alpha(r, z)}{\partial z} &= - \left[\left(\frac{z_1}{r_1^3} + \frac{z_2}{r_2^3} \right) \left(\frac{1}{r_1 + r_2 - \delta\ell} - \frac{1}{r_1 + r_2 + \delta\ell} \right) \right. \\
&\quad \left. + \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \left(\frac{z_1}{r_1} + \frac{z_2}{r_2} \right) \left(\frac{1}{(r_1 + r_2 - \delta\ell)^2} - \frac{1}{(r_1 + r_2 + \delta\ell)^2} \right) \right] \\
\frac{\partial\phi(r/\sigma)}{\partial r} &= \frac{1}{\sigma} 2.5 \left(\frac{r}{\sigma} \right)^{1.5} e^{-(r/\sigma)^{2.5}} \left[2.5 - 1.5 \left(\frac{r}{\sigma} \right)^{2.5} \right]
\end{aligned} \tag{9}$$

The vorticity along the vortex filament and normal (in the radial direction) may then be computed as:

$$\begin{aligned}
\omega_z(\bar{x}, t) &= -\frac{\Omega}{4\pi} \left[\left(r_{ij} \frac{\partial\alpha(r, z)}{\partial r} + 2.0\alpha(r, z) \right) \phi(r/\sigma) + r_{ij} \alpha(r, z) \frac{\partial\phi(r/\sigma)}{\partial r} \right] \\
\omega_r(\bar{x}, t) &= -\frac{\Omega}{4\pi} \left(r_{ij} \frac{\partial\alpha(r, z)}{\partial z} \right) \phi(r/\sigma)
\end{aligned} \tag{10}$$

A known approximation in the art is the use of only the vortex stretching and advection term, so the evolution of vorticity may be approximated as:

$$\frac{\partial\bar{\omega}}{\partial t} + \bar{u} \cdot \bar{\nabla} \bar{\omega} = (\bar{\omega} \cdot \bar{\nabla}) \bar{u} \tag{11}$$

1 The second term on the left is due to advection and the
2 right hand side is due to stretching. By advecting the blobs and
3 filaments with the local flow velocity, the advection term is
4 automatically included. Also, the horseshoe vortices may be
5 modeled by a series of filaments that are connected. Since the
6 endpoints of the filaments are advected, circulation is
7 automatically conserved using the relation:

$$9 \quad (\delta l \sigma)_{t+\Delta t} = (\delta l \sigma)_t \quad (12)$$

10

11 This, effectively, implicitly includes the vortex stretching
12 term. Since the circulation is constant, lengthening the
13 filament will reduce the radius and, as can be seen from (8), the
14 vorticity will increase.

15 The remaining question is how to treat the surface. In the
16 present formulation, it is proposed that the surface effect is
17 assumed to be included in the mean flow. Therefore, the vortex
18 filaments will be advected due to the mean experimental or
19 computational inflow as well as the perturbed inflow due to the
20 blobs and filaments themselves.

21 The vortex filaments will need to be initialized. Various
22 schemes may be used to accomplish this. For cases where the
23 turbulent intensity is known, the circulation may be adjusted so
24 the maximum induced velocity matches the maximum turbulent
25 velocity. If the wake energy is specified, the kinetic energy

1 will provide another means to initialize the flow. The blobs
2 will be initialized to provide an additional random component.

3 The effective turbulent intensity and velocity spectra data
4 due to the vortex blobs and filaments may be computed and
5 compared with the experimental database. The size, strength and
6 distribution of the vortex filaments will then be adjusted to
7 match the experimental data with the vortex blobs providing and
8 additional random component to mimic the higher wavenumber
9 behavior. Once qualitative and quantitative agreement is
10 reached, the data will be deemed suitable for the full flow
11 simulation.

12 FIG. 3 shows a flow chart of the computational process. The
13 routine is initialized in step 20. In step 22, boundary
14 conditions are obtained. This may be done via experimental,
15 empirical or computational fluid dynamics. Maximum turbulent
16 velocity and basic flow structure is required to initialize the
17 vorticity field. These data can also be used to validate the
18 model. The next step 24 defines the geometry of the flow domain
19 where the vorticity is defined. In step 26, based on step 22,
20 the turbulent inflow velocity spectral data are obtained and
21 scaled to the local flow domain. In step 28 filament elements
22 and blob elements are distributed over the flow geometry
23 established in step 24. Filament elements are provided at the
24 surface and blobs are provided further out in the flow field as

1 discussed above. Initialization of the vortical flow then
2 follows.

3 After the flow is initialized, the current velocities and
4 vorticities are calculated for each element in step 30, and the
5 time step is advanced in 32. In step 34, flow is evolved by
6 moving elements as dictated by the calculated vorticities and
7 velocities. The elements are then evolved according to the eqn.
8 (11). Here, the element centroids (in the case of blobs) or
9 element end points (in the case of filaments) are advected based
10 on the computed velocity. Stretching is accounted for in the
11 case of filaments by applying eqn. (12). Direct computation of
12 the viscous diffusion may also be implemented according to the
13 methods outlined in US Patent number 6,424,923.

14 After the flow is evolved, a check in step 36 is made to see
15 if additional elements are required upstream. Elements are added
16 to preserve the definition required for the model. If so,
17 elements are added and initialized in step 38. Elements that
18 have advected far downstream are eliminated in step 40 as they
19 will have little effect on the flow velocities in the region of
20 interest. Also, during step 42 of the flow process, elements may
21 be stretched or compressed requiring division or amalgamation to
22 maintain spatial resolution and numerical accuracy. If a
23 filament exceeds twice its original length, it is divided into
24 two equally sized elements. Also, elements that are separated by
25 a very short distance (defined according to minimum spatial

1 resolution requirements) may be combined to conserve angular and
2 linear momentum. Flow routine is looped in step 44 for the
3 period of interest, and terminated by step 46.

4 Data recording the development of the flow field as
5 represented by the element locations can be displayed while being
6 generated and/or recorded for analysis.

7 More detail concerning vortex filament initialization is
8 given with reference to the planned application, modeling flow
9 into an undersea vehicle propulsor having rotors and stators.
10 The vortex filaments are initialized with a circulation, radius
11 and length and placed upstream of the propulsor rotor immediately
12 downstream of the stator. Vortex filaments representing the hull
13 boundary layer and the stator wakes are treated separately. FIG.
14 4A and FIG. 4B show an example of a single boundary layer vortex
15 loop at successive downstream stations 50A, 50B, 50C, 50D and
16 50E. Downstream direction in the FIGS. is indicated by arrow 52.
17 The boundary layer vortices are modeled using single vortex loops
18 50 that encircle the vehicle hull 54. Each vortex loop 50
19 consists of approximately two hundred vortex filaments.
20 Superimposed on the ring shape is a sinusoidal perturbation.
21 This perturbation is intended to model the horseshoe vortices.
22 This perturbation results in a number of effective horseshoe
23 vortices that are inclined at angles between 40 to 50 degrees
24 relative to the hull surface 54. The number of perturbations for
25 each loop is randomly varied between 20 and 60 and an additional

1 random perturbation of 0.01 is introduced in the axial and radial
2 direction that results in the differing inclination angle. At
3 each time step ($\Delta t = 0.025$), eleven of these vortex loops are
4 evenly stacked normal to the surface beginning at a normalized
5 distance of 0.05 above the hull surface extending out a distance
6 of 0.25. As the individual vortex loops are advected downstream
7 from 50A to 50E, FIG. 4A and FIG. 4B show that the mean shear
8 boundary layer flow stretches the vortex filaments creating
9 elongated hairpin vortices. To maintain resolution, filaments
10 are divided equally after they double in length based on their
11 initial value. Vortex loops are removed after they have advected
12 two propeller radii downstream. For a typical calculation, the
13 boundary layer consists of 1,000 loops and 200,000 filaments. To
14 match the mean velocity profile of the hull boundary layer a mean
15 circulation of 0.002 is used for each filament. To better
16 achieve the profile, the first two layers have circulations 1.5
17 times the mean value and the outer four layers have circulations
18 half the mean value. To provide an additional random component
19 modeling the turbulence, the circulation and radius are randomly
20 perturbed by 50% of the mean value.

21 The model of the stator wake vorticity is intended to
22 capture both the shed boundary layer vorticity and wake vorticity
23 due to lift. To accomplish this, a simple vortex pair model is
24 used. The wake thickness is known from the experimental results
25 and the vortex lattice model provides the circulation of the

1 vorticity (due to lift) initially shed into the wake. What is
2 not provided is the effect of the boundary layer vorticity shed.
3 Each vortex loop consists of 36 filaments where the filament
4 control points correspond to the control points at the stator
5 trailing edge from the vortex lattice code. The filament centers
6 corresponding to an upper and lower loop are separated a distance
7 of 0.5 wake thicknesses (t_{wake}) in the axial direction and 0.25
8 t_{wake} in the circumferential direction. Additionally, each
9 filament control point is randomly perturbed an additional
10 distance of 0.125 t_{wake} in the axial direction and 0.05 t_{wake} in
11 the circumferential direction. To achieve the correct velocity
12 defect, a filament circulation of 0.005 is used. A circulation
13 differential corresponding to the vortex lattice output of the
14 wake circulation is used to model the stator lift effect. To
15 introduce an additional component of turbulence, each filament's
16 circulation and radius is perturbed by 10% of its mean value.

17 Finally, vortex blobs are used to introduce a higher
18 wavenumber turbulent component. These blobs are introduced
19 immediately downstream of the stator at each time step with 300
20 blobs in the circumferential direction and six radial stations
21 for 1800 blobs each time step. Typically, this results in
22 approximately 100,000 additional blobs in the boundary layer.
23 Each blob has a radius of 0.01 with the radius perturbed by 50%
24 of its mean value. Blob circulation is randomly initialized
25 between ± 0.0005 .

1 The effective turbulent intensity and velocity spectra data
2 due to the vortex blobs and filaments were computed and compared
3 with the experimental database. The size, strength and
4 distribution of the vortex filaments were adjusted to match the
5 experimental data with the vortex blobs providing an additional
6 random component to mimic the higher wavenumber behavior. Once
7 qualitative and quantitative agreement was reached, the data were
8 deemed suitable for the full flow simulation.

9 FIG. 5 shows velocity vectors 56 calculated in accordance
10 with the disclosed method. In the actual application, velocity
11 vectors are color coded based on the axial velocity. The vectors
12 are plotted at the filament and blob control points. The
13 filament initiation plane 58, the plane where experimental data
14 were collected 60, and the outflow plane 62 where points are
15 removed are clearly delineated.

16 The present methodology has several advantages over previous
17 methods to simulate turbulent flows. First of all, the vorticity
18 representation of the flow is more physically descriptive of the
19 instantaneous flow field compared with ensemble averaging
20 techniques (RANS) or large eddy simulation (LES) that rely on
21 turbulence models. Advecting the vorticity as a material element
22 reduces the likelihood of creating artificial diffusion of the
23 coherent structures. Utilizing empirical data to match the
24 initial inflow allows for proper representation of the spectral
25 behavior of the flow. Finally, the by evolving the flow in time,

1 the entire flow is spatially correlated. The mathematical
2 formulation for this particular set of vortex filaments is also
3 unique.

4 While the present invention has been particularly described,
5 in conjunction with a specific preferred embodiment, it is
6 evident that many alternatives, modifications and variations will
7 be apparent to those skilled in the art in light of the foregoing
8 description. It is therefore contemplated that the appended
9 claims will embrace any such alternatives, modifications and
10 variations as falling within the true scope and spirit of the
11 present invention.

2

3 A METHOD TO SIMULATE UNSTEADY TURBULENT
4 FLOWS USING A VORTICITY BASED METHOD

5

6

ABSTRACT OF THE DISCLOSURE

7 A computerized method for determining the velocity field of
8 a three-dimensional fluid flow over a submerged body. Inflow
9 velocities, turbulence, spectral behavior is provided over a body
10 geometry. The method uses filament elements near the body and
11 blob elements at a distance from the body. Velocity and
12 vorticity are calculated at each time increment and then the
13 elements are evolved based on the calculated values. Blob
14 elements are moved using the centroid of the blob, and filament
15 elements are moved by use the ends of the filaments. New
16 elements are added as required upstream in the flow field. The
17 time is incremented and the routine is repeated for a period of
18 interest, providing a model of the flow field about the body.
19 Hairpin filaments can be modeled by attaching multiple filaments
20 end to end.

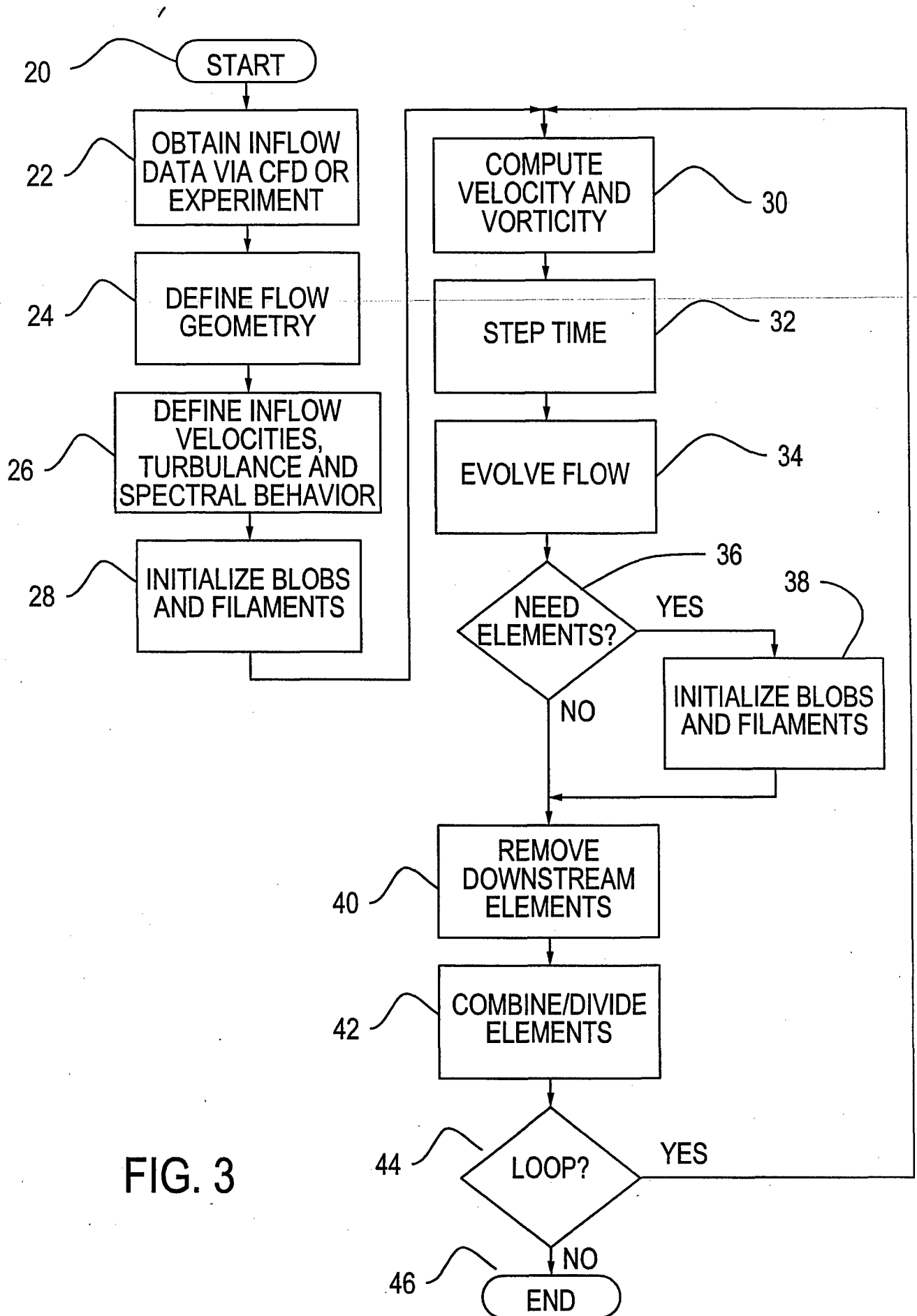


FIG. 3

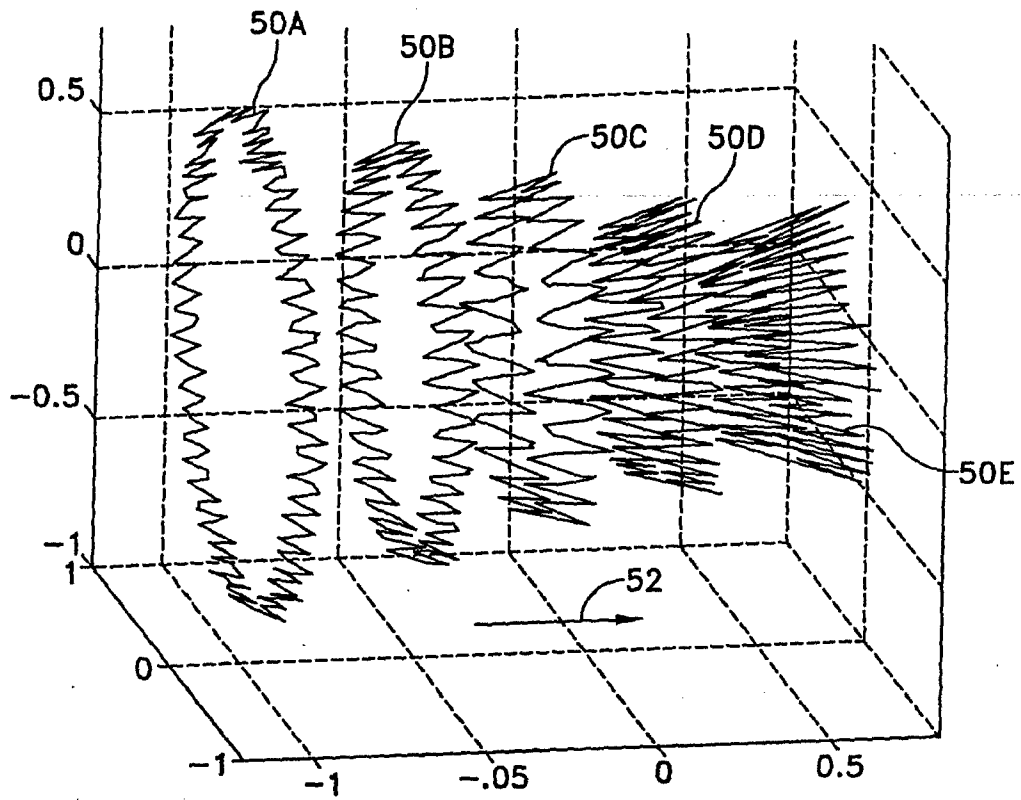


FIG. 4A

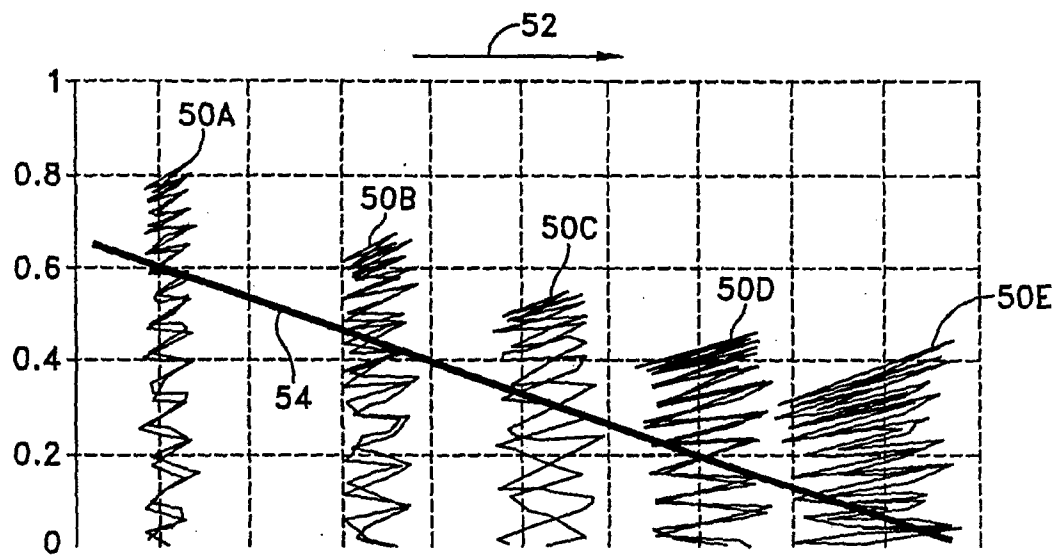


FIG. 4B

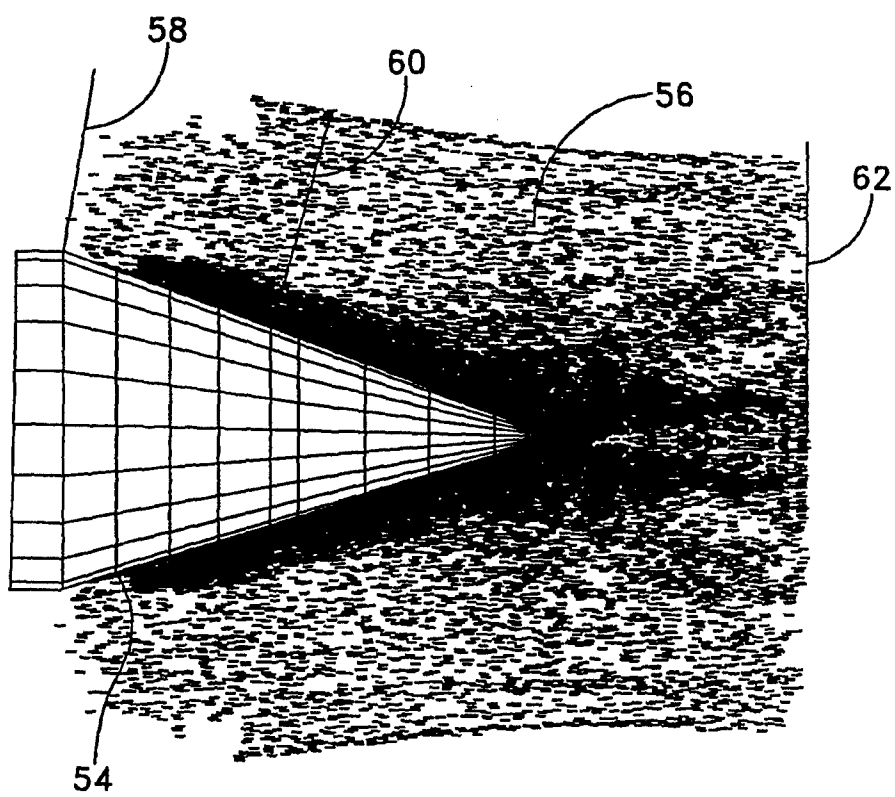


FIG. 5