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COMBINED WEDGE-FLAP FOR IMPROVED SHIP POWERING

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

The present invention relates to the hydrodynamics of marine vessels, more particularly to adjuncts, appendages and auxiliary devices for affecting same.

Structural additions of various kinds and configurations have been implemented for various types of marine vessels in order to improve powering performance. Some very small pleasure craft and planing boats have been provided with adjustable trim flaps (trim tabs) for controlling the trim. As for combatant vessels, during World War II some small German ships were provided with stern wedges for the purpose of improving powering

performance. Until the early 1980's, however, neither stern wedges nor stern flaps were known to be pursued by anyone for combatant ships of the frigate/destroyer size (approximately 3,000 to 10,000 Long Tons displacement).

In the 1980's some foreign navies began to successfully apply stern wedges to larger ships up to the frigate size. In addition, the U.S. Navy began to explore possibilities regarding auxiliary structure for enhancing powering performance of larger (frigate/destroyer sized) ships. See Righter, J.R., Jr. and R. Compton, "The Effects of a Bow bulb and Stern Wedge on a Large Waterplane, Transom Sterned Hullform," U.S. Naval Academy Report, EW-25-82 (October 1982), incorporated herein by reference; Karafiath, G. and S.C. Fisher, "The Effect of Stern Wedges on Ship Powering Performance," Naval Engineers Journal (May 1987), incorporated herein by reference. Based on the research efforts presented in the paper by Karafiath and Fisher, *supra*, the U.S. Navy designed the *Arleigh Burke* (DDG 51) Class destroyer with a stern wedge inlaid into the hull; many of these twenty-seven designed DDG 51's are already built. Model tests demonstrated that implementation of such a stern wedge resulted in a reduction of power of up to a maximum of about 6% at speeds above 24 knots.

A stern wedge design was initially attempted by the U.S. Navy for the FFG 7 frigate class; however, in the course of model testing it was discovered that a stern flap was more effective than a stern wedge on this class. The model tests demonstrated approximately a 5% decrease in delivered power at speeds of 20

knots and above. In 1989, a stern flap was designed and retrofitted by the U.S. Navy on the *USS Copeland* frigate (FFG 25). Analysis of the ship trials data for the *USS Copeland* frigate having a retrofitted stern flap indicated an 8% power saving, somewhat greater than the model test results, and increased top end speed. See Cusanelli, D.S., and W.M. Cave, III, "Effect of Stern Flaps on Powering Performance of the FFG-7 Class," Marine Technology, Vol. 30, No. 1 (Jan. 1993), incorporated herein by reference.

A stern flap design was selected through model testing for full scale retrofit to the PC 1 Class Patrol Coastal. The retrofit of a stern flap on the *Shamal* (PC 13) showed that the flap would reduce required delivery power by 5.6% and increase top speed and range on this class. See Cusanelli, D.S., "Stern Flap Powering Performance on the PC 1 Class Patrol coastal, Full Scale Trials and Model Experiments," PATROL '96 Conference, New Orleans, Louisiana (December 1996), incorporated herein by reference. Subsequent to the above-noted investigation regarding the *Shamal*, the U.S. Navy has tested various stern flaps at CDNSWC on several models of various ship types. These model tests have not only shown that significant energy savings are possible with stern flaps, but have also provided valuable insights into stern flap operational mechanisms. See, e.g., the paper by Cusanelli (December 1996), *supra*; Cusanelli, D.S., and K.M. Forgach, "Stern Faps for Enhanced Powering Performance," Twenty-Fourth American Towing Tank Conference, College Station,

Texas (November 1995), incorporated herein by reference.

Although the aforedescribed results have been encouraging, the U.S. Navy has continued to seek better ways for improving ship powering performance.

SUMMARY OF THE INVENTION

In view of the foregoing, it is a principal object of the present invention to reduce the shaft power required to propel a ship, thereby reducing the engine fuel consumption.

Prior to the present invention, wedges and flaps have represented discrete concepts and have been used exclusively of each other. This invention features the novel implementation of a wedge-flap combination for enhancing the powering performance of marine vessels.

The present invention is especially contemplated for utlization in connection with large combatant ships of frigate/destroyer dimensions. This invention was originally motivated by the U.S. Navy's desire to even further improve the powering performance of the above-mentioned *Arleigh Burke* (DDG 51) Class AEGIS Guided Missle Destroyer, Flight 1 design, which has already been provided with an inlaid transom wedge.

In accordance with the present invention, a combination is provided for affecting the hydrodynamics of a hullform having a hull aftside and a hull underside which converge at a stern corner. The inventive combination comprises wedge means and flap

means. The wedge means is below the hull underside and at least substantially before the hull aftside. The flap means is at least substantially behind the hull aftside. The wedge means has a wedge undersurface and a wedge aft-periphery. The flap means has a flap undersurface and a flap fore-periphery. The wedge aft-periphery and the flap fore-periphery are each contiguous the stern corner. The hull underside has associated therewith an approximate longitudinal bisector passing therethrough. The wedge undersurface and the flap undersurface are each obliquely oriented with respect to the approximate longitudinal bisector.

For many inventive embodiments, it is propitious to dispose the wedge portion and the flap portion at approximately equal angles with respect to the slope of the local centerline buttock, thereby practically effecting a consolidated bottom wedge-flap surface which unites the individual bottom surfaces of the wedge and the flap, and which is characterized by approximately the same angle with respect to the slope of the local centerline buttock.

The main advantage of the inventive combined wedge-flap is that it affords a greater reduction in shaft power than does either the wedge acting alone or the flap acting alone. Solitary wedge operation, solitary flap operation and inventive combined wedge-flap operation share similar hydrodynamic principles, except that the inventive combined wedge-flap results in greater powering improvement in comparison with either the solitary wedge or the solitary flap.

The key parameters which affect the performance of a solitary wedge, a solitary flap or an inventive combined wedge-flap, are: (i) the chord length(s); (ii) the span length(s); (iii) the angle(s) relative to the buttock lines (e.g., buttock centerline); (iv) the planform shape(s); and, (v) the thickness shape(s). Of particular note regarding shape are the configurational fairing details (e.g., at locations outboard, near the transom's bottom edge, etc.).

Other objects, advantages and features of this invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the present invention may be clearly understood, it will now be described, by way of example, with reference to the accompanying drawings, wherein like numbers indicate the same or similar components, and wherein:

FIG. 1 is a highly diagrammatic, partial (stern), side elevation view of a typical hullform of a large combatant ship.

FIG. 2 is a view, similar to the view shown in *FIG. 1*, of the ship shown in *FIG. 1*, wherein the hullform is provided with a stern wedge.

FIG. 3 is a view, similar to the view shown in *FIG. 1*, of the ship shown in *FIG. 1*, wherein the hullform is provided with

a stern flap.

FIG. 4 is a view, similar to the view shown in *FIG. 1,* of the ship shown in *FIG. 1*, wherein the hullform is provided with an inventive combined wedge-flap.

FIG. 5 is a schematic, partial (stern), perspective view of a U.S. Navy DDG 51 Class ship (destroyer) model which has been provided with an inventive combined wedge-flap; this design has been selected for the U.S. Navy DDG 51 Class destroyer fleet.

FIG. 6 is another schematic, partial (stern), perspective view of the ship model shown in *FIG. 5*.

FIG. 7 is a schematic, partial (stern), perspective view of a ship model, similar to the ship model and view shown in *FIG. 5*, also showing the selected inventive combined wedge-flap design.

FIG. 8, *FIG. 9* and *FIG. 10* are schematic plan views of various shapes of the stern flap portion of the inventive combined wedge-flap which the U.S. Navy tested using ship models such as shown in *FIG. 5*, *FIG. 6* and *FIG. 7*.

FIG. 11 is a schematic, partial (stern), side elevation view of a ship model such as shown in *FIG. 5*, *FIG. 6* and *FIG. 7*, showing installation of the stern flap portion of the inventive combined wedge-flap.

FIG. 12 is a schematic, partial (stern), side elevation view of a U.S. Navy DDG 51 Class ship which is provided with an inventive combined wedge-flap such as the inventive combined wedge-flap shown in *FIG. 9*.

FIG. 13 is a schematic, partial (port and stern), top plan

view of the ship which is shown in *FIG. 10* to be provided with an inventive combined wedge-flap.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to *FIG. 1*, ship **18** is navigating a sea having waterline **20**. Hull **22** of ship **18** includes main deck **24**, (local) buttock centerline **26**, hull bottom **28** and transom **30**. Deck **24** and transom **30** meet at upper aft transverse edge **27**; i.e., upper aft transverse edge **27** is the corner (junction) formed by the intersection of transom **30** and deck **24**. Hull bottom **28** and transom **30** meet at lower aft transverse edge **29**; i.e., lower aft transverse edge **29** is the corner (junction) formed by the intersection of transom **30** and hull bottom **28**.

With reference to *FIG. 2*, *FIG. 3* and *FIG. 4*, each of these partial profiles displays additional structure in the afterbody of hull **22**. As shown in *FIG. 2*, stern wedge **32** starts at a location forward of transom **30** and ends at transom **30**. The entire wedge **32** is under hull bottom **28**. As shown in *FIG. 3*, stern flap **34** starts at lower aft edge **29** and extends to a location aft of transom **30**. As shown in *FIG. 4*, inventive combined stern wedge-flap **36** starts at a location forward of transom **30** and extends past transom **30** to a location aft of transom **30**.

In *FIG. 2*, wedge **32** has upper wedge surface **38** and lower wedge surface **40**. Wedge angle α_W is the angle of lower wedge

surface **40** in relation to (local) buttock centerline **26**. Wedge chord c_W is the fore-and-aft (longitudinal) wedge length as measured across lower wedge surface **40**. In *FIG. 3*, flap **34** has upper flap surface **42** and lower flap surface **44**. Flap angle α_F is the angle of lower flap surface **44** in relation to (local) buttock centerline **26**. Flap chord c_F is the fore-and-aft (longitudinal) flap length as measured across lower flap surface **44**.

The point of departure for each of wedge **32** and flap **34** is in the vicinity of edge **29**. Wedge **32** differs from flap **34** principally in the respect that wedge **34** is situated under hull bottom **28**, and does not extend aft of transom **30**; typically, wedge **32** is inlaid into the plating of hull bottom **28**. By contrast, lower flap surface **44** is an extension of the hull bottom **28** surface, flap **34** extending aft of transom **30**.

In *FIG. 4*, inventive combined wedge-flap **36** comprises wedge **32** portion and flap **34** portion. Inventive combined wedge-flap **36** thus essentially manifests the respective contours of wedge **32** and flap **34** shown in *FIG. 2* and *FIG. 3*, respectively, including upper surfaces **38** and **42** and lower surfaces **40** and **44**. *FIG. 4* is representative of the many inventive embodiments wherein lower wedge surface **40** and lower flap surface **44**, to a substantial degree, are merged or integrated in approximately coplanar fashion, or in nearly coplanar, approximately parallel-stepped fashion, thereby effectively forming lower wedge-flap surface **46**; meanwhile, upper wedge surface **38** and upper flap surface **42** have

essentially retained their separate identities.

Wedge-flap angle $\alpha_{W\text{-}F}$ is the angle of lower wedge-flap surface **46** in relation to (local) buttock centerline **26**. Wedge-flap chord $c_{W\text{-}F}$ is the fore-and-aft (longitudinal) inventive wedge-flap length as measured across lower wedge-flap surface **46**. In this illustration, wedge-flap angle $\alpha_{W\text{-}F}$, wedge angle α_W and flap angle α_F are all approximately equal; wedge-flap chord $c_{W\text{-}F}$ approximately equals the sum of wedge chord c_W and flap chord c_F.

Transom **30**, substantially rectilinear, approximately defines imaginary infinite plane *t*. In inventive practice, generally, infinite plane *t* is an expedient approximation, albeit in some applications transom **30** will be characterized by a degree of curvilinearity in the vertical direction and/or the horizontal direction. It can be conceived that plane *t* bounds or limits wedge **32** in *FIG. 2*, flap **34** in *FIG. 3*, wedge **32** portion in *FIG. 4*, and flap **34** portion in *FIG. 4*.

In *FIG. 2*, wedge **32** is situated beneath hull bottom **28** so that lower wedge surface **40** is disposed at a downward wedge angle α_W with respect to centerline **26**. Wedge **32** extends between a location proximate edge **29** and a location forward of infinite plane *t*. In *FIG. 3*, flap **34** projects from the stern so that lower flap surface **44** is disposed at a downward flap angle α_F with respect to centerline **26**. Flap **34** extends between a location proximate edge **29** and a location aft of infinite plane *t*.

Analogously, in *FIG. 4*, wedge **32** portion is situated beneath hull bottom **28** so that lower wedge surface **40** is disposed at a

downward wedge angle α_W with respect to centerline **26**. Wedge **32** portion extends between a location proximate edge **29** and a location forward of infinite plane *t*. Flap **34** portion projects from the stern so that lower flap surface **40** is disposed at a downward flap angle α_F with respect to centerline **26**. Flap **34** portion extends between a location proximate edge **29** and a location aft of infinite plane *t*.

Wedge angle α_W, flap angle α_F and wedge-flap angle $\alpha_{W\text{-}F}$ are each referenced to the slope of local centerline buttock **26**. In *FIG. 4*, since wedge angle α_W approximately equals flap angle α_F, with some approximation lower wedge surface **40** can be considered to effectively blend with lower flap surface **44** so as to form lower wedge-flap surface **46** which is disposed at a downward wedge-flap angle $\alpha_{W\text{-}F}$ with respect to centerline **26**, whereby wedge-flap angle $\alpha_{W\text{-}F} \approx$ wedge angle $\alpha_W \approx$ flap angle α_F.

The physics pertaining to the operation of the inventive combined stern-wedge entails the combined effects of stern wedges and stern flaps. Hydrodynamic principles behind the operation of stern wedges are explained in the paper, *supra*, of May 1987 by Karafiath and Fisher. Hydrodynamic principles behind the operation of stern flaps are explained in the paper, *supra*, of November 1995 by Cusanelli and Forgach, and in the paper, *supra*, of December 1996 by Cusanelli. The principles of operation are similar for the stern wedge, the stern flap and the inventive combined wedge-flap, with the notable exception the the inventive combined wedge-flap results in greater powering improvement than

does either the wedge acting alone or the flap acting alone. The stern wedge, stern flap, or inventive combined stern wedge-flap is itself a drag producer under virtually all conditions; however, the beneficial interaction with the hull results in a net decrease in ship resistance and in required delivered power.

To briefly elaborate on the hydrodynamics involved, operation of any one of the three configurations (the stern wedge, the stern flap, the inventive combined stern-flap) causes the flow to slow down under the hull at a location extending from the aftmost portion of the ship to a point generally forward of the propellers. This decreased flow velocity will cause an increase in pressure, which in turn causes the following: (i) a drag on the flap, wedge or inventive combined wedge-flap; (ii) a forward thrust on the ship's afterbody; (iii) an upward force on the ship's afterbody; (iv) a decreased flow velocity and an increased pressure.

The drag on the flap, wedge or inventive combined wedge-flap increases the powering. The forward thrust which is generated on the ship's afterbody is greater than the drag (on the flap, wedge or inventive combined wedge-flap), and is responsible for most of the powering benefit; it has been estimated that, in some cases, this thrust accounts for more than 50% of the powering benefit. The upward force which is generated on the ship's afterbody results in a lowered trim angle and a slight rise in the center of gravity relative to the water surface. Generally, this upward force effect contributes 10% to 20% to the decreased powering.

The decreased flow velocity and increased pressure extends to the top of the propeller disk; this is, in general, favorable to the powering (and cavitation) performance of the propeller.

In addition, the stern wave system is modified. The waves behind the ship appear flatter with a smaller rooster tail. Model test measurements show that the wave resistance is decreased. This effect may account for 10% to 25% of the decreased power. For solitary flap or inventive combined wedge-flap configurations, there is a physical lengthening of the ship's wetted length, which further enhances this wave resistance reduction.

A distinction should be drawn between the inventive hydrodynamic principles for a destroyer-type hull versus those for a high speed planing (or semi-planing) patrol-type boat. Planing boats, which attain speeds in the range of $F_n = 0.9$, experience large changes in trim (as much as two degrees), whereas destoyers exhibit trim changes on the order of only 0.2 degrees. The dynamic lift of a planing boat, and associated induced drag, are greatly affected by changes in trim. It is principally this change in trim which can reduce the planing boat's resistance. On a destroyer, the dynamic lift effects, compared to the total ship displacement, are much less than on a planing boat. It is a modification in the flow field around the afterbody of a ship which causes the principal changes in the resistance and the powering performance on a displacement hull.

Reference now being made to *FIG. 5*, *FIG. 6* and *FIG. 7*,

resistance tests were conducted by the U.S. Navy in September 1996 at the Naval Surface Warfare Center, Carderock Division (NSWCCD), using DTMB (David Taylor Model Basin) ship Model 5513, for purposes of selecting an appropriate inventive combined wedge-flap design for the DDG 51 Class. Ship Model 5513, built to a scale ratio $\lambda = 20.2609$, is representative of the *Arleigh Burke* (DDG 51) Class Flight I, AEGIS Guided Missile Destroyer, which has LBP ("Length Between Perpendiculars") equal to 466 feet and Beam equal to 59.24 feet; hence, Model 5513 has LBP equal to 23 feet and Beam equal to 2.924 feet. Generally, the dimensions stated hereinbelow in relation to Model 5513 are full scale dimensions.

The uniqueness of the present invention resides especially in the combination of a stern flap with a stern wedge. To the inventors' knowledge, the combination of a stern wedge and a stern flap had never been tested by anyone prior to these U.S. Navy ship model tests. Presumably, the prevailing assumption in the art has been that both a stern wedge and a stern flap act on the same fluid, and hence that a combination of a stern wedge and a stern flap would provide no more benefit than would either a stern wedge acting alone or a stern flap acting alone, and may even be counterproductive.

These ship model tests were performed by the U.S. Navy at the fleet displacement of 8,900 tons. As depicted in *FIG. 5*, *FIG. 6* and *FIG. 7*, DDG 51 ship model **18m** is equipped with inventive combined wedge-flap **36**, which includes wedge **32** portion

and flap **34** portion. The inventive wedge-flap **36** configuration shown in *FIG. 5* through *FIG. 7* was ultimately selected for the DDG 51 destroyer fleet on the basis of these tests.

The design of stern wedge **32** portion for the DDG 51 destroyer had been established by the U.S. Navy previous to these ship model tests. Stern wedge **32** portion on the DDG 51 Class Flight I ship is designed to be an integral part of (inlaid into) the full scale hullform; however, at model scale, stern wedge **32**, as shown, was a separate installed appendage. Wedge angle α_W for the designed DDG 51 stern wedge **34** portion was 13 degrees.

As revealed by *FIG. 5* through *FIG. 7*, wedge **32** portion is symmetrically tapered slightly in both lateral directions so as to be thickest at centerline **26** (not shown but envisioned in *FIG. 5* through *FIG. 7*), and to then be gradually thinned out toward both wedge extremities **47**. Hence, wedge angle α_W typically is considered to represent such measurement where centerline **26** bisects wedge **32** portion, and is greater than any wedge **32** angle which would be measured at a noncentric location of wedge **32** portion. Upper wedge surface **38** flushly engages hull bottom **28**, conforming to the curvilinear shape of hull bottom **28**; in particular, wedge extremities **47** curve in conformance with the radial bilge shape of hull bottom **28**.

With reference to *FIG. 8*, *FIG. 9* and *FIG. 10*, each of three stern flap **34** portion designs was evaluated during these tests in combination with, and situated behind, stern wedge **32** portion. Flap chord c_F differed for each flap **34** portion design. Flap **34**

portion shown in *FIG. 8* had flap chord c_F = 2.3 feet (0.7 meters), which represented about 0.5% of the ship LBP. Flap **34** portion shown in *FIG. 9* had flap chord c_F = 3.5 feet (10.7 meters), which represented about 0.75% of the ship LBP. Flap **34** portion shown in *FIG. 10* had flap chord c_F = 4.7 feet (1.43 meters), which represented about 1.0% of the ship LBP.

Flap span s_F is the port-and-starboard (transverse) flap length. Each flap **34** portion shown in *FIG. 8* through *FIG. 10* had a flap span s_F = 24 feet (8.35 meters), which was the maximum reasonably possible flap span s_F across transom **30** without flap **34** portion impinging on the wake off the corners of transom **30**, and without requiring significant curvature of flap **34** portion around the bilge radius. In order to simplify construction and reduce full scale flap manufacturing costs, flap ends **48** simply were rounded (radiused) so as to, in plan view, have a radius equal to flap chord c_F.

Referring to *FIG. 11*, stern flap **34** portion was a custom fit metal plate attached at the stern of ship model **18m**; the flap **34** portion on the real DD 51 ship is expected to have a more "structural" upper flap surface **44**. The gap between flap **34** portion and transom **30** was bridged by small fairing strip **50**, fastened to ship model **18m** adjacent lower aft transverse edge **29**, thereby preventing crossflow and pressure loss between transom **30** and the forward edge of flap **34** portion. Using angle adjusting bracket **52**, flap angle α_F was tested in $\pm$ 5 degree increments relative to lower wedge surface **40**, in other words in $\pm$ 5 degree

increments with respect to a 13 degree flap angle α_F which equaled the 13 degree wedge angle α_W. For illustrative purposes, flap angle α_F is shown in *FIG. 11* to be adjusted to equal 20 degrees.

The stern flap **34** portion design shown in *FIG. 10* was selected to be the one best suited for integration with the existing stern wedge **32** portion. This decision was premised on the desirability of maximizing potential annual energy savings, and was based on the experimental model test data and DDG 51 Class ship speed-time profile. The measured resistance for each stern flap **34** portion design, at each angle variation, across the speed range, was weighted by the DDG 51 speed-time mission profile, in order to generate an annual time-averaged resistance. These annual time-averaged resistance calculations were then compared to that of the baseline (wedge **32** portion, only) DDG 51. Based on this resistance comparison, stern flap **34** portion was selected to have flap chord c_F = 1.0% ship LBP (4.7 feet, 1.4 meters), and to be situated at flap angle α_F = 13 degrees, parallel to lower wedge surface **42** of stern wedge **32** portion.

Accordingly, now referring to *FIG. 12* and *FIG. 13*, the inventive combined wedge-flap **36** configuration which was selected for the DDG 51 destroyer fleet was characterized by the following parametric values: wedge-flap angle $\alpha_{W\text{-}F}$ = 13 degrees, in conformity with a 13 degree wedge angle α_W and a 13 degree flap angle α_F; wedge-flap chord $c_{W\text{-}F}$ = 7.87 feet (2.4 meters); wedge chord c_W = 3.17 feet (0.966 meters); flap chord c_F = 4.7 feet (1.43 meters); flap span s_F = 24 feet (8.35 meters); wedge span

s_W, the port-and-starboard (transverse) wedge length, is nearly coextensive with the length of lower aft transverse edge **29**. From the perspective shown in *FIG. 13*, it appears that the delimitation or demarcation between wedge **32** portion and flap **34** portion has approximate coincidence with lower aft transverse edge **29**.

In inventive practice, the design of an inventive combined wedge-flap involves sizing both the wedge and flap portions, and selecting the most suitable geometry. The critical parameters for design geometry are: wedge angle α_W; flap angle α_F; wedge-flap angle $\alpha_{W\text{-}F}$; wedge chord c_W; flap chord c_F; wedge-flap chord $c_{W\text{-}F}$; wedge span s_F; flap span s_F.

All the U.S. Navy model-tested stern wedges, stern flaps and inventive combined wedge-flaps demonstrated similar trends in terms of the critical design parameters and their effects on ship resistance. At the low speeds, there is a resistance penalty associated with the device. At some intermediate speed, which varies with design, there is a "crossover" to reduced resistance. At higher speeds, there is further resistance reduction. In general, a longer chord length has a greater low speed resistance penalty, and the crossover point to reduced resistance is delayed to a greater ship speed, but the high speed resistance reduction is also greater. The same is generally true for increased angle: Low speed resistance penalty and crossover speed increase, while high speed resistance reduction also improves.

Initial inventive combined wedge-flap design includes

determining the span across the transom. The inventive combined wedge-flap should span the maximum reasonable width possible across the transom, without impinging on the wake off the corners of the transom, and without requiring significant curvature around the bilge radius. In some instances, transom observations without the inventive combined wedge-flap installed can be invaluable in determining this maximum span.

Selection of a final inventive combined wedge-flap shape also includes determining planform shape with special attention to the outboard edges, transverse thickness variations, the use or elimination of a hard corner at the outboard edges, and the detailed fairing into the hull. For many inventive embodiments, a simple radiused corner treatment (in plan view) should be chosen to simplify construction and reduce full scale manufacturing costs. Experience indicates that the wedge portion should have a tapered thickness, with the greatest thickness (and thus the greatest angle) at its centerline. The tapering also allows for a favorable smooth transition to be achieved near the turn of the bilge, and elimination of undesrable hard corners. In inventive practice, attention to these additional design details will generally minimize low speed powering penalties, without compromising high speed performance.

The design of an inventive combined wedge-flap is affected greatly by mission requirements as well as hullform design. A compromise must be reached between improving high speed performance and minimizing low speed penalties. The particular

ship's speed-time mission profile will dictate the relative importance of the high speed and low speed performances under consideration.

The inventive combined wedge-flap **36** design which was selected by the U.S. Navy for the DDG 51 as aforedescribed was then tested in both resistance and powering. The powering experiments were conducted with model propellers representative of the 17 feet (5.18 meters) diameter DDG 51 Class Flight I, Advanced Technology Demonstration (ATD) propeller design by the U.S. Navy at NSWCCD.

The resistance and the powering were each analyzed in terms of the following ratio:

$$\frac{\text{SHIP HAVING INVENTIVE COMBINED WEDGE FLAP}}{\text{SHIP HAVING NO WEDGE AND NO FLAP}}$$

According to the above ratio, the wedgeless, flapless ship thus represented the "baseline hull."

The experimental results showed that the reduction in delivered power by the inventive combined wedge-flap was approximately 1 to 3 percent greater than the reduction in resistance across the speed range. This has generally been the case for stern wedge and stern flap designs which have been model-tested to date by the U.S. Navy.

As demonstrated by **Table 1**, found hereinbelow, the predicted delivered power reduction of the inventive combined wedge-flap (vis-a-vis' a "no wedge - no flap" configuration) is quite

marked, averaging about 6.25 percent over the speed range. A negative value in **Table 1** indicates a decrease in shaft power; a positive value in **Table 1** indicates an increase in shaft power. In the range of the DDG 51 maximum speed, the delivered power reduction is nearly 12 percent. It is noted that, since the full scale DDG 51 Flight I hull already features an inlayed stern wedge, a "no wedge - no flap" configuration is academic for such vessel.

The powering reduction for the inventive combined wedge-flap far exceeded what was achievable using either a solitary wedge or a solitary flap. It is theorized that this superior performance of the inventive combined wedge-flap was at least partially attributable to the effectively longer combined chord length, viz., wedge-flap chord $c_{W\text{-}F}$, of 7.87 feet (2.4 meters). The Model 5513 test data, collected during the selection process for the stern flap portion of the inventive combined wedge-flap intended for the DDG 51 destroyer, suggests that the longer effective chord length (wedge-flap chord $c_{W\text{-}F}$) resulted in better performance of the model.

To recapitulate, the predictions set forth in **Table 1** are based on standard model self-propulsion tests conducted by the U.S. Navy at NSWCCD. The wedge-only data derived from tests using Model 5422, conducted in 1986. The flap-only data derived from tests using Model 5422-4, conducted in 1995. The inventive combined wedge-flap data derived from tests using Model 5513, conducted in September 1996. Except for small geometric

variations, each of these models represents the 466 foot long DDG 51 and has a scale factor of 20.261. All of these tests conducted by the U.S. Navy were state-of-the-art ship model tests implementing standard accepted naval architectural ship model test procedures for predicting ship powering performance.

Table 1. Percent Change in Delivered Power on DDG 51 Ship Model

SHIP SPEED (KNOTS)	PERCENT CHANGE IN DELIVERED POWER DUE TO WEDGE ONLY	PERCENT CHANGE IN DELIVERED POWER DUE TO FLAP ONLY	PERCENT CHANGE IN DELIVERED POWER DUE TO COMBINED WEDGE-FLAP
0	+0.8	+1.4	+2.2
12	+0.6	+0.2	+0.8
14	+0.5	-0.7	-0.2
16	+0.3	-1.1	-0.8
18	-1.4	-2.7	-4.0
20	-4	-3.8	-7.6
22	-5	-4.6	-9.4
24	-5.7	-6.0	-11.3
26	-5.9	-5.6	-11.2
28	-4.8	-5.5	-10.1
30	-5.7	-6.2	-11.6
32	-6	-6.3	-11.9

The selected DDG 51 stern flap **34** portion design, when inventively installed in combination with the inlaid stern wedge **32** portion, exhibited an increased power in the range of 1.4% at 10 knots; this is less than the 3 to 4% usually associated with stern flaps installed alone. It is theorized that this was at least partially attributable to the stern flow already having been deflected to the 13 degree angle by the presence of stern wedge **32** portion; stern flap **34** portion is, in effect, at a zero degree angle of attack relative to this deflected flow. In general, flaps at zero degree positions fare well at low speeds.

As of now, twenty-seven DDG 51's have been equipped, according to the U.S. Navy's plan, with an inlaid stern wedge. It is expected that the inventive retrofit with the combined wedge-flap will result in a powering improvement over the wedge-only mode. For instance, **Table 1** indicates that, at 30 knots, the inventive combined wedge-flap saves 11.6% in power relative to a ship having neither a wedge nor a flap; however, the power saving relative to the existing DDG 51 ships which are already equipped with a wedge is 11.6% - 5.7% = 5.9%.

The yearly power (and fuel) saving is calculated by applying the saving at a given ship speed to the number of hours that the ship operates at that speed as specified in the ship's mission profile. According to such calculations, the speed-time-averaged powering improvement (over the existing wedge-only mode) for the DDG 51 is 4.6%. According to engine fuel flow calculations, the annual fuel saving will be 3.8%, corresponding to $112,000 cost

saving per ship. Retrofit costs are expected to be about $50,000, excluding dry docking costs. Thus, the cost of the inventive combined wedge-flap will be offset by less than one year's fuel saving. The total fuel saving for all 27 ships over their lifetime will be on the order of $100 million.

As previously noted herein, the results of the U.S. Navy's testing using ship Model 5513 suggest that the longer effective chord length (wedge-flap chord $c_{W\text{-}F}$) associated with inventive combined wedge-flap **36** yields better ship powering performance than either a shorter chord length (wedge chord c_W) associated with solitary wedge **32** would yield or a shorter chord length (flap chord c_W) associated with a solitary flap **34** would yield. This observation gives rise to the conjecture, dismissed by the inventors as explained hereinbelow, that either a very large solitary wedge **32** or a very large solitary flap **34** would represent a viable alternative to inventive combined wedge-flap **36**. A large wedge **32** alone or a large flap **34** alone would have practical as well as hydrodynamic disadvantages.

Inventive combined wedge-flap **36** is structurally advantageous relative to a large solitary flap **34** in that inventive combined wedge-flap **36** is a compact unit which minimizes the bending moments. For the DDG 51 destroyer, wedge-flap chord $c_{W\text{-}F}$ is 7.9 feet, with 4.7 feet (corresponding to flap chord c_F) cantilevered behind transom **30**. An equivalent size solitary flap **34** (having flap chord c_F = 7.9 feet) would be cantilevered 7.9 feet behind transom **30**, and consequently would

have larger bending moments.

Furthermore, such a large solitary flap **34** (e.g., having flap chord c_F = 7.9 feet) might be impractical. The 4.7 foot cantilevered portion (corresponding to flap chord c_F) of inventive combined wedge-flap **36** would be constructed by effectuating techniques similar to those effectuated for the simple construction of a bilge keel on this size ship. By contrast, the 7.9 foot chord solitary flap **34** would require more sophisticated construction and analysis of forces. Indeed, even battleships do not have 7.9 foot bilge keels. The structural weight of such a large solitary flap **34** would be greater than that of an equivalently chorded inventive combined wedge-flap **36**.

Moreover, such a large solitary flap **34** could interfere with some ship operations. The large solitary flap **34** would extend beyond upper aft tranverse edge **27** and might interfere with some towed array operations. The overall ship length would be increased.

A hydrodynamic disadvantage of a large solitary wedge **32** is the resultant significantly increased immersion of transom **30**, leading to poor performance at low speeds (below 18 knots). A large solitary wedge **32** having a 7.9 wedge chord c_W, for example, would start 7.9 feet forward of transom **30**; however, because of the slope of buttock centerline **26** (or of the buttocks, in general) such a fore starting point would be lower than the fore starting point of the wedge **32** portion of inventive combined wedge-flap **36**, assuming wedge angle α_W = wedge-flap angle $\alpha_{W\text{-}F}$.

In other words, if wedge angle α_W (the inclination of lower flap surface **40** of large solitary wedge **32**) approximately equals wedge-flap angle $\alpha_{W\text{-}F}$ (the inclination of lower wedge-flap surface **46** of inventive combined wedge-flap **36**), then the trailing position of large solitary wedge **32** will be lower than that of inventive combined wedge-flap **36** because of the lower forward starting point.

Hence, a large solitary wedge **32** would be characterized by increased immersion of transom **30** and poor low speed performance. Model ship tests which the U.S. Navy has conducted using varying solitary wedge sizes have demonstrated that the larger solitary wedges have associated therewith increased low speed powering penalties. The low speed performance is critical because the ship operates at these low speeds a high percentage of the time.

From the retrofit application standpoint for a ship such as the DDG 51, a large solitary wedge **32** is undesirable because of the increased construction costs as compared with the construction costs for an inventive combined wedge-flap **36**. Only the flap **34** portion of inventive combined wedge-flap **36** need be added to the existing solitary wedge **32** in order to make the inventive combined wedge-flap **36** configuration. Flap **34** portion of inventive combined wedge-flap **36** is easy to construct because such construction involves the welding of plates which are at large angles to each other and to transom **30**; conventional welding techniques can be used in such construction. On the other hand, the welding of the leading edge of a large solitary

wedge **32** would require that a more expensive and intricate "slot weld" technique be implemented, due to the relatively small 10 to 15 degree angle (corresponding to wedge angle α_W with respect to centerline **26**) which solitary wedge **32** forms relative to hull bottom **28**. Retrofit of a large solitary flap **34** is not a practical option for the DDG 51, as this would require removal of the existing solitary wedge **32** (which is inlaid into the hull bottom **28** plating).

The inventive combined wedge-flap can be applied to a new ship design or retrofitted to an existing ship design. An inventive combined wedge-flap can have the greatest impact on ship design if its performance benefit is recognized early in the design process. Regardless, it is to be expected that the decrease in power associated with the inventive combined wedge-flap will exceed the decrease in power assiciated with either a solitary wedge or a solitary flap.

The inventive combined wedge-flap is appropriate for retrofit to several U.S. Navy cruiser/destroyer and frigate type hulls other than the DDG 51. For instance, early 1980's ship model tests on the DD 963/CG 47 hullform demonstrated a maximum 2% powering improvement due to a solitary stern wedge; this solitary wedge design was not adopted, and these ships as of today do not have a stern wedge. Incidentally, examination of this wedge design indicates that it was a somewhat crude design by today's standards; it is believed that a wedge designed today would give at least a 4% reduction in power.

Model powering experiments were recently conducted by the U.S. Navy on the same DD 963/CG 47 hullform. A solitary stern flap (i.e., with no wedge) demonstrated a maximum 9% reduction in power. An inventive combined wedge-flap was not tested in relation to this model; however, it is believed that an inventive combined wedge-flap would result in a maximum power reduction greater than 9%.

Generally speaking, a stern wedge, a stern flap or an inventive combined stern wedge-flap will begin to manifest powering reduction effectiveness at lower ship speeds and will manifest maximum powering reductions at higher ship speeds. In the case of the above-noted testing by the U.S. Navy of the DD 963/CG ship model having a solitary flap, the solitary flap commenced powering reduction effectiveness in the 14 to 16 knots speed range, and the maximum power reduction occurred at 29 to 30 knots. It is believed that an inventive combined wedge-flap would commence powering reduction effectiveness at lower speeds than the 14 to 16 knots associated with the solitary flap configuration.

Other embodiments of this invention will be apparent to those skilled in the art from a consideration of this specification or practice of the invention disclosed herein. Various omissions, modifications and changes to the principles described may be made by one skilled in the art without departing from the true scope and spirit of the invention.

ABSTRACT

The inventive combination of a stern wedge and a stern flap demonstrates hydrodynamic properties which, for purposes of enhancing the powering performance of a ship, are superior to those of either a solitary stern wedge or a solitary stern flap. For many inventive embodiments, the stern wedge portion's lower surface and the stern flap portion's lower surface are slanted at approximately equal angles with respect to the buttock centerline, thereby optimally consolidating the stern portion's lower surface and the flap portion's lower surface so as to effectively create an overall hydrodynamic lower surface which is slanted approximately at one and the same angle.

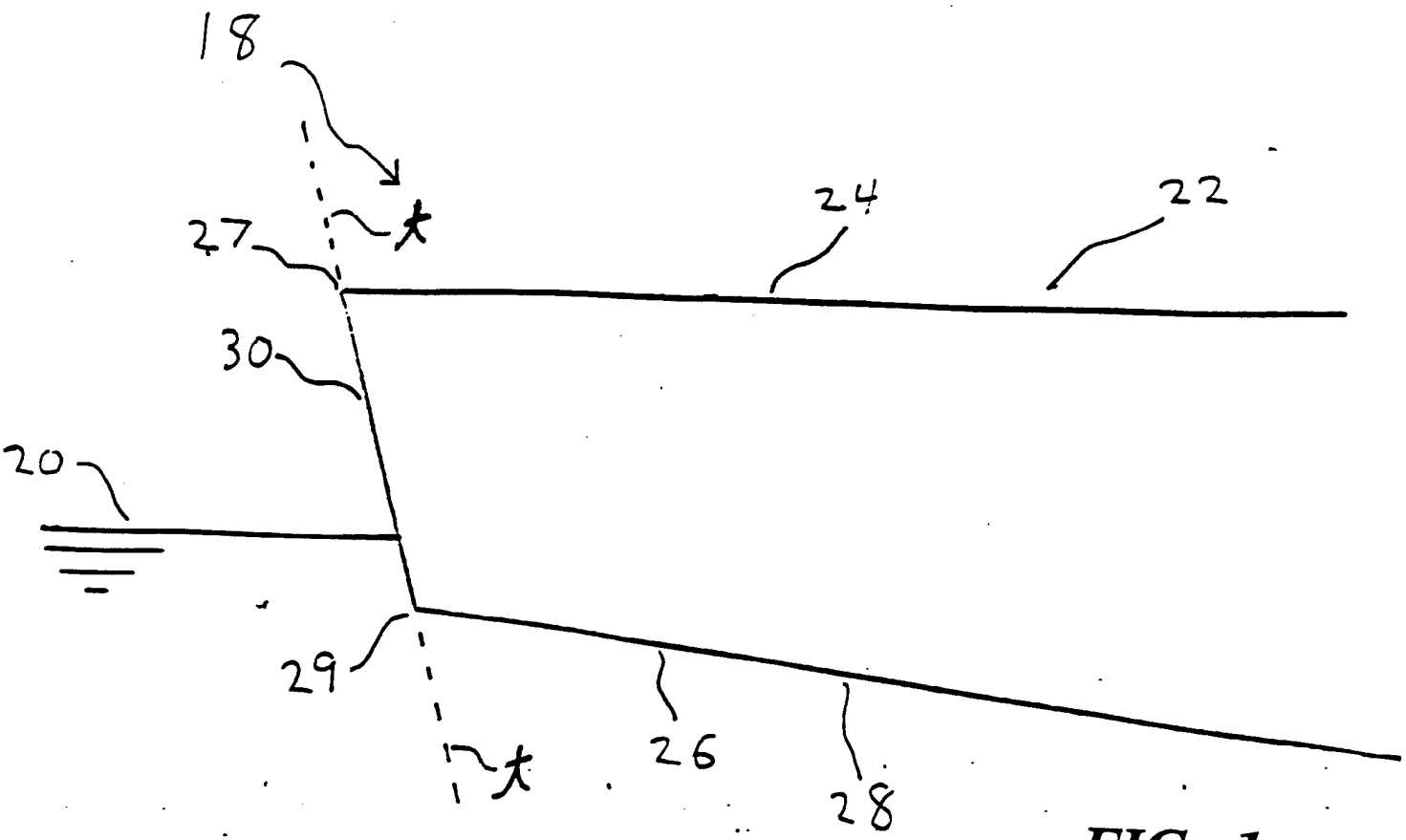
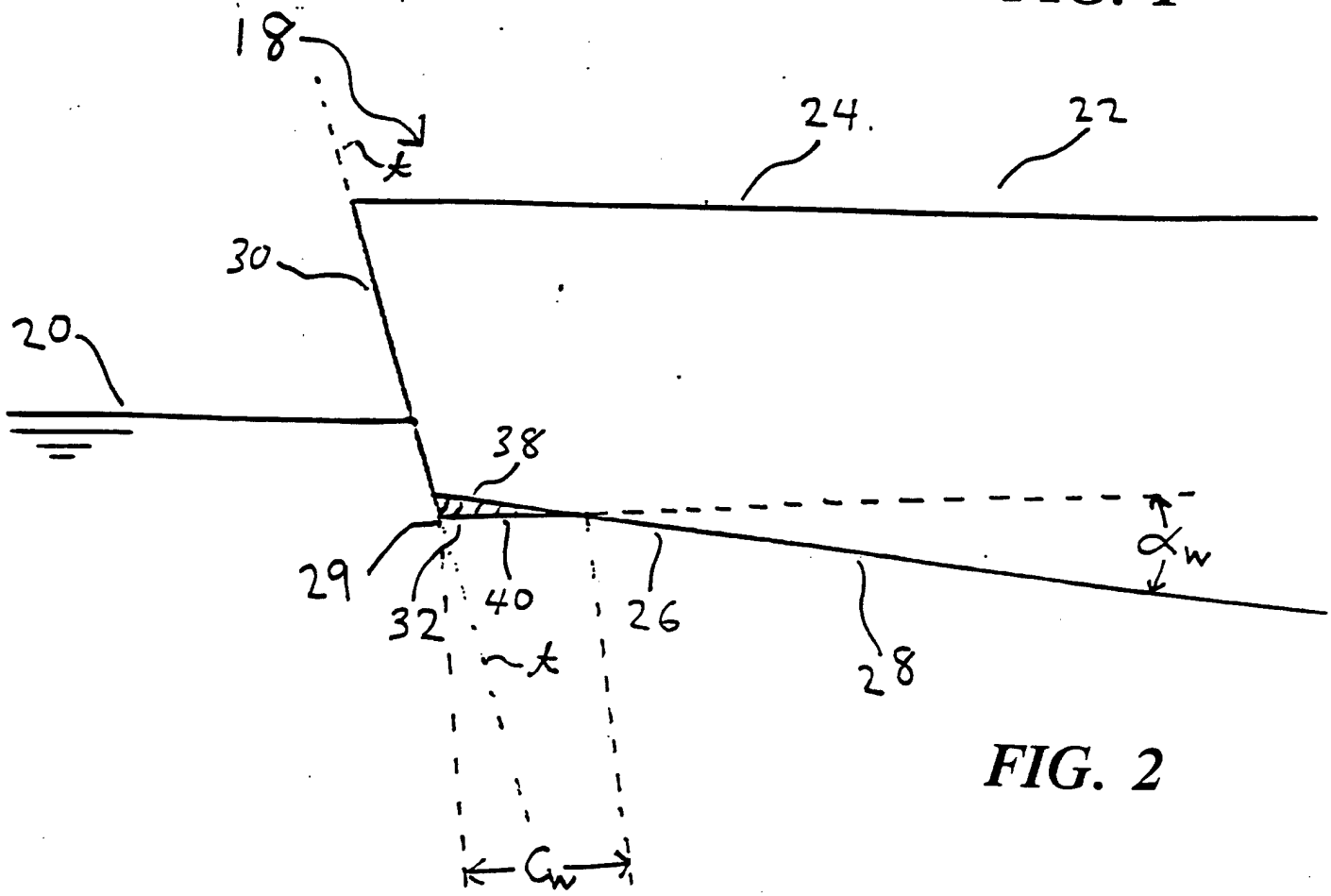

18
t
27
24
22
30
20
29
26
t
28

FIG. 1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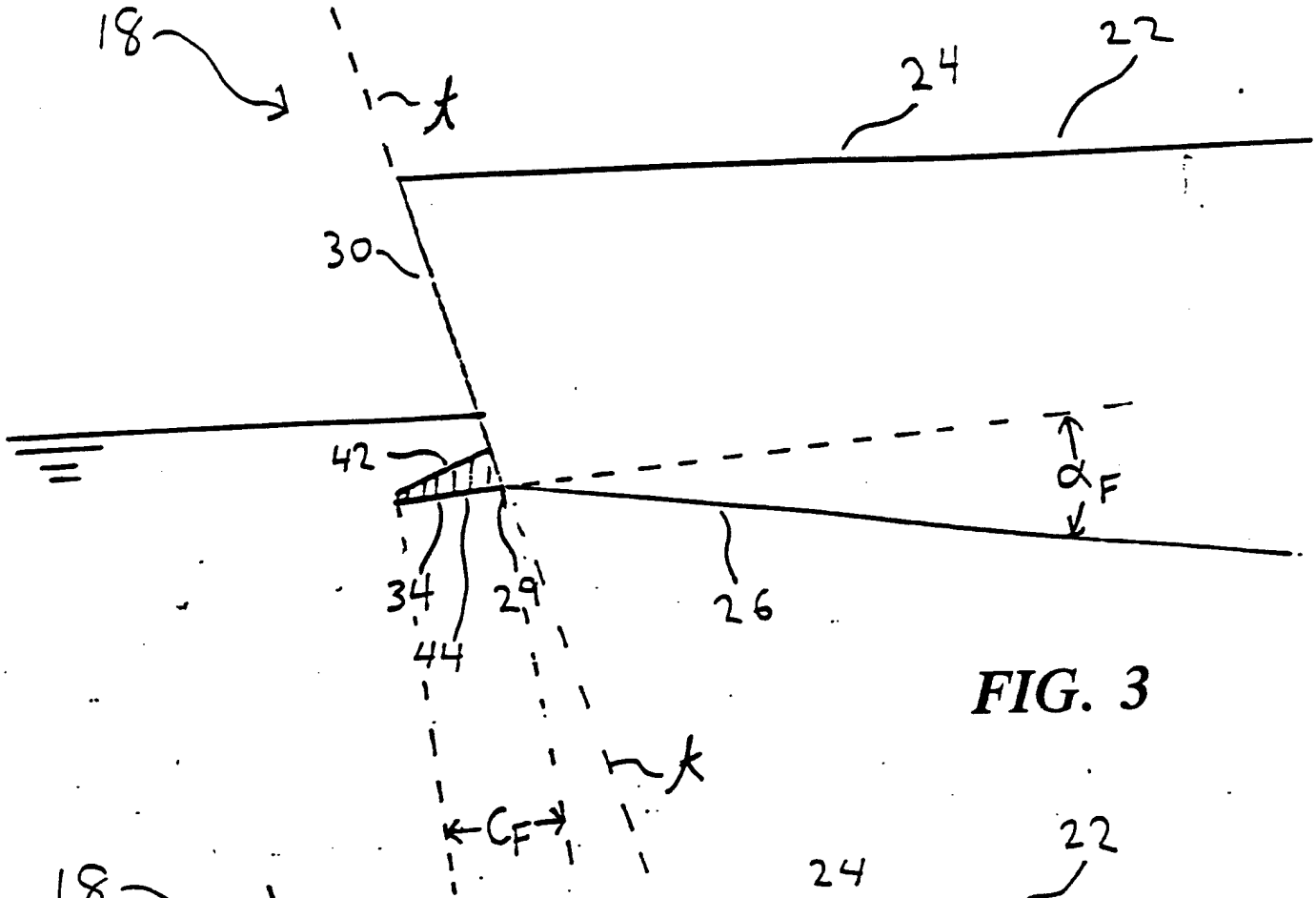
22
30
20
38
29
32
40
26
t
28
α_w
C_w

FIG. 2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t
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22
30
42
α_F
34
29
26
44
t
C_F

FIG. 3

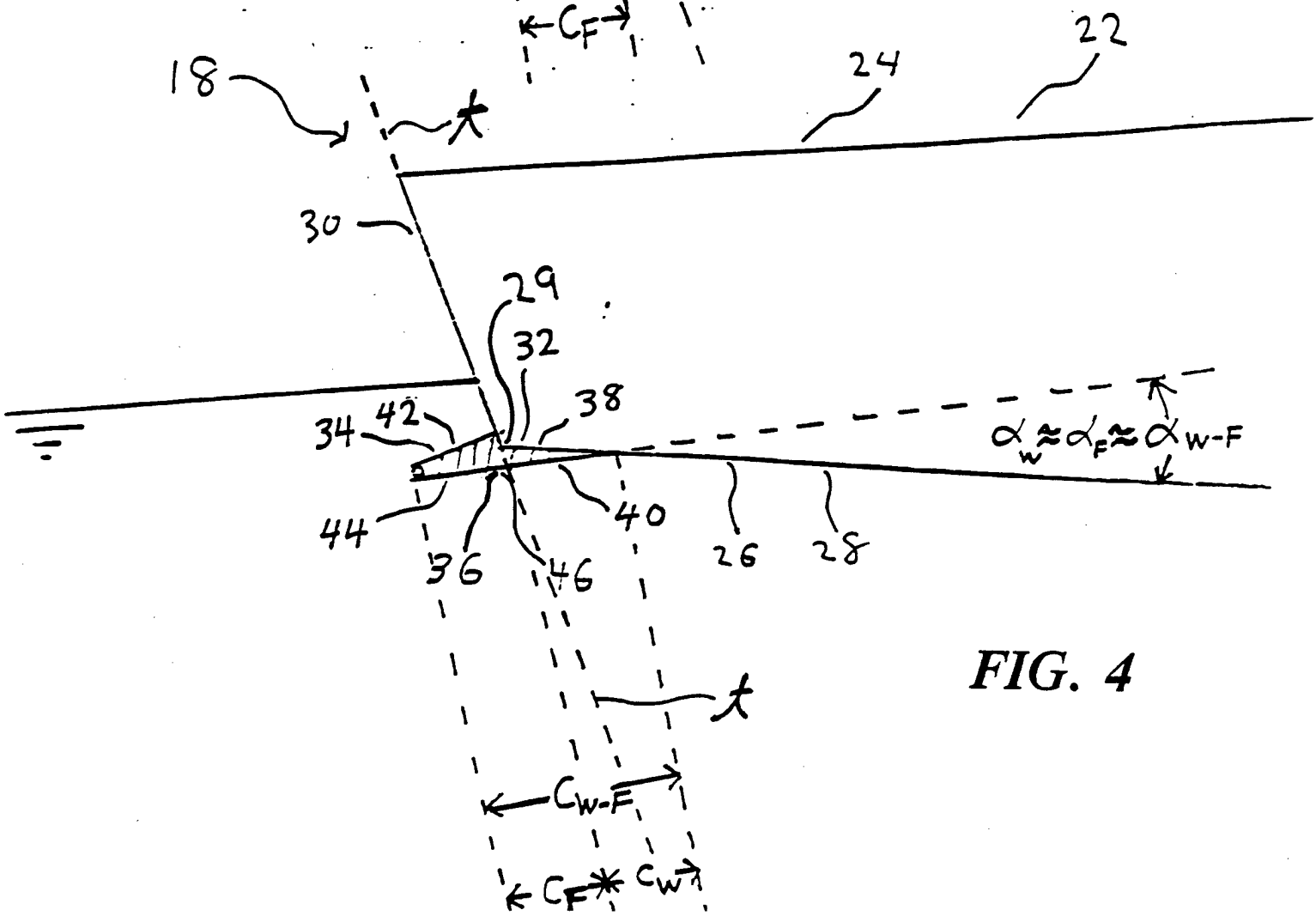
18
t
24
22
30
29
32
38
34
42
$\alpha_w \approx \alpha_F \approx \alpha_{W-F}$
44
40
36
46
26
28
t
C_{W-F}
C_F
C_W

FIG. 4

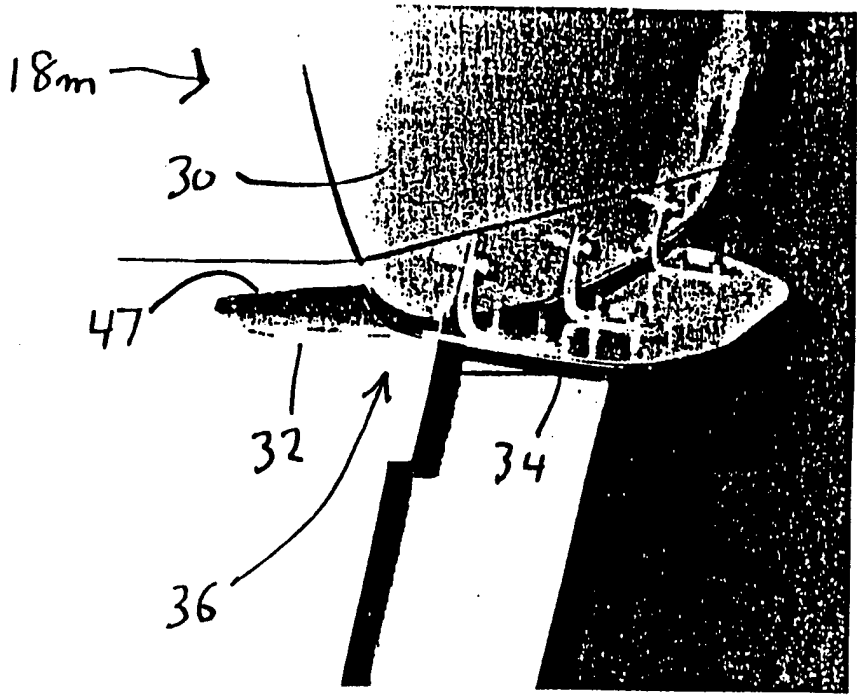

FIG. 5

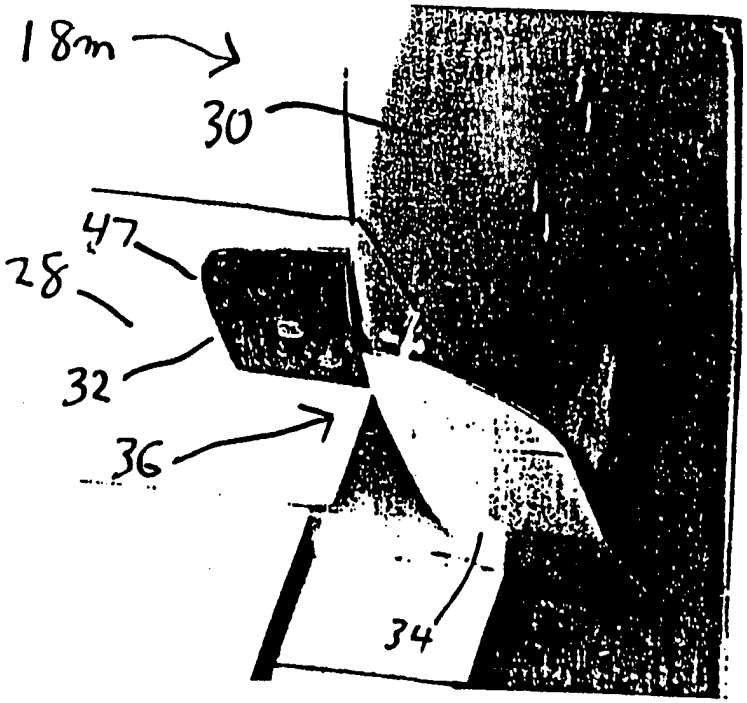

FIG. 6

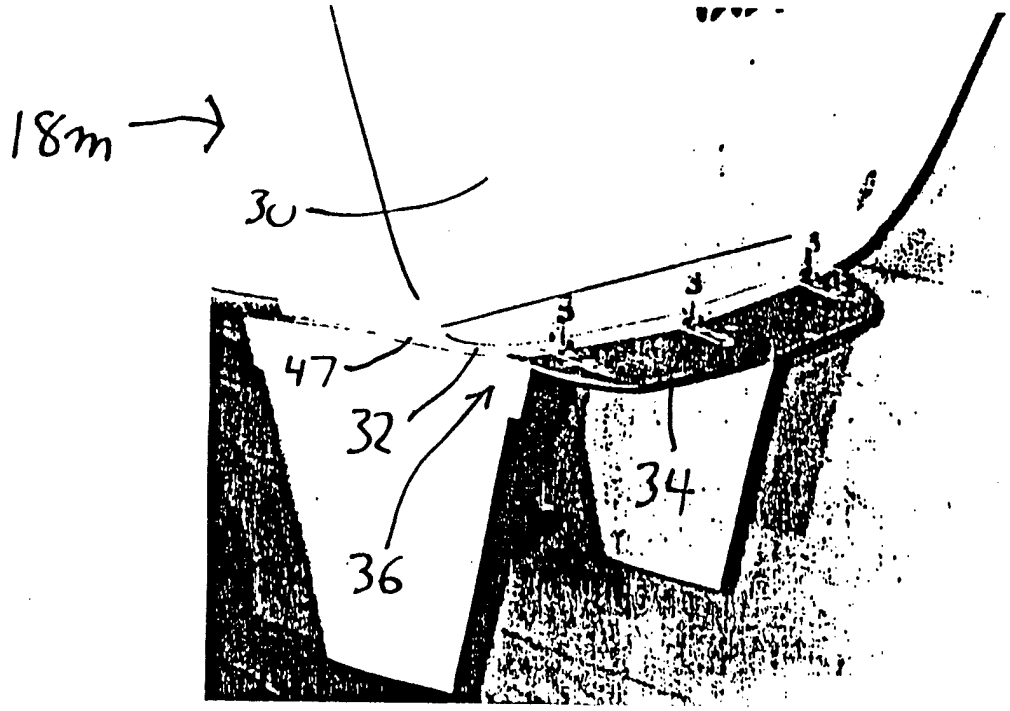

FIG. 7

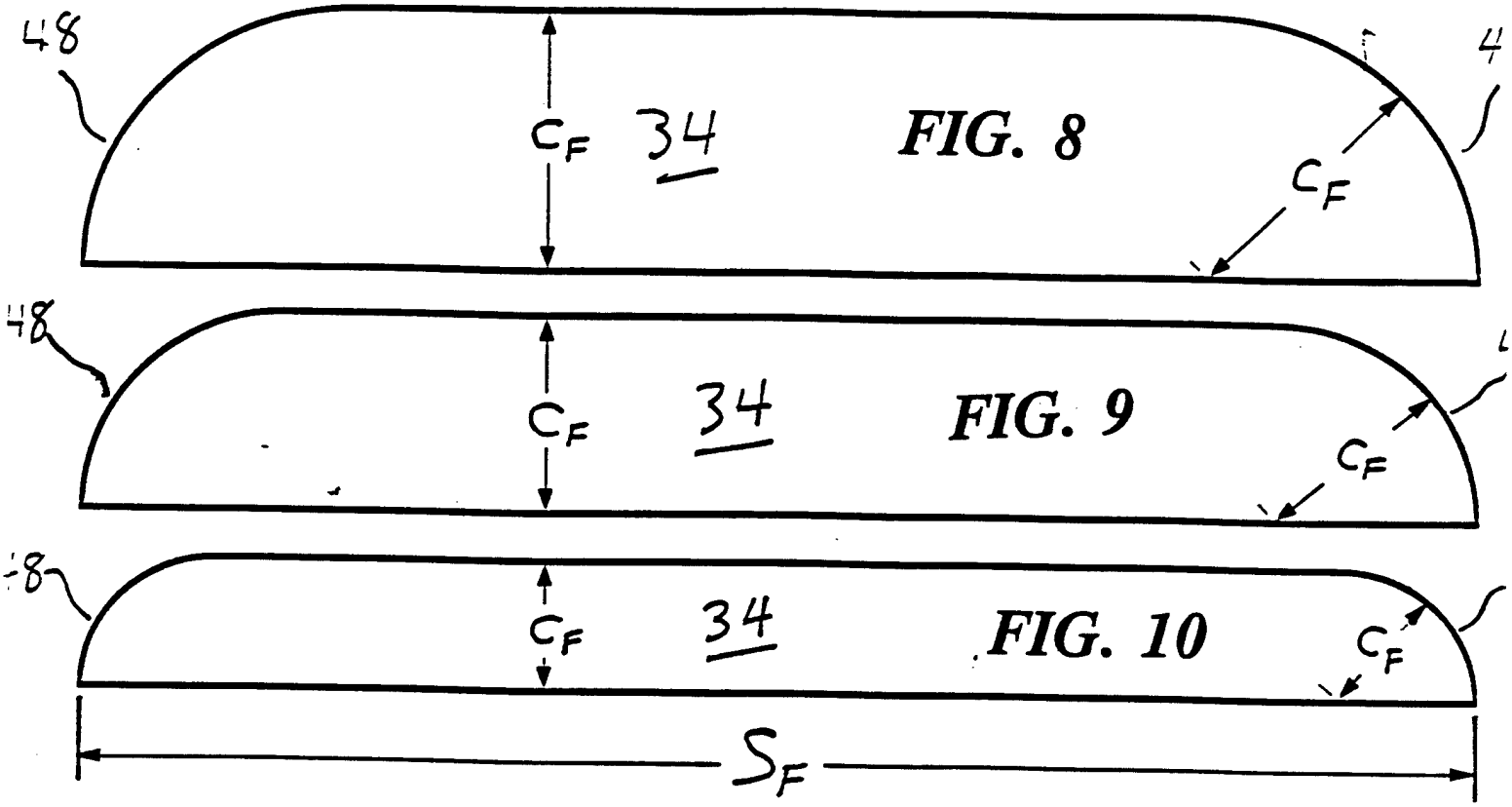

FIG. 8

FIG. 9

FIG. 10

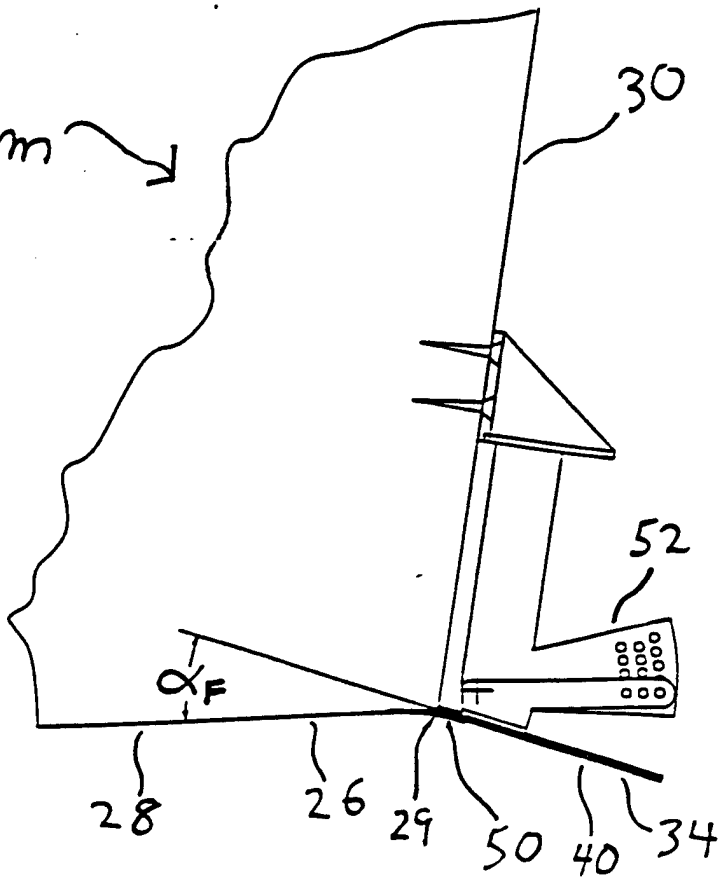

FIG. 11

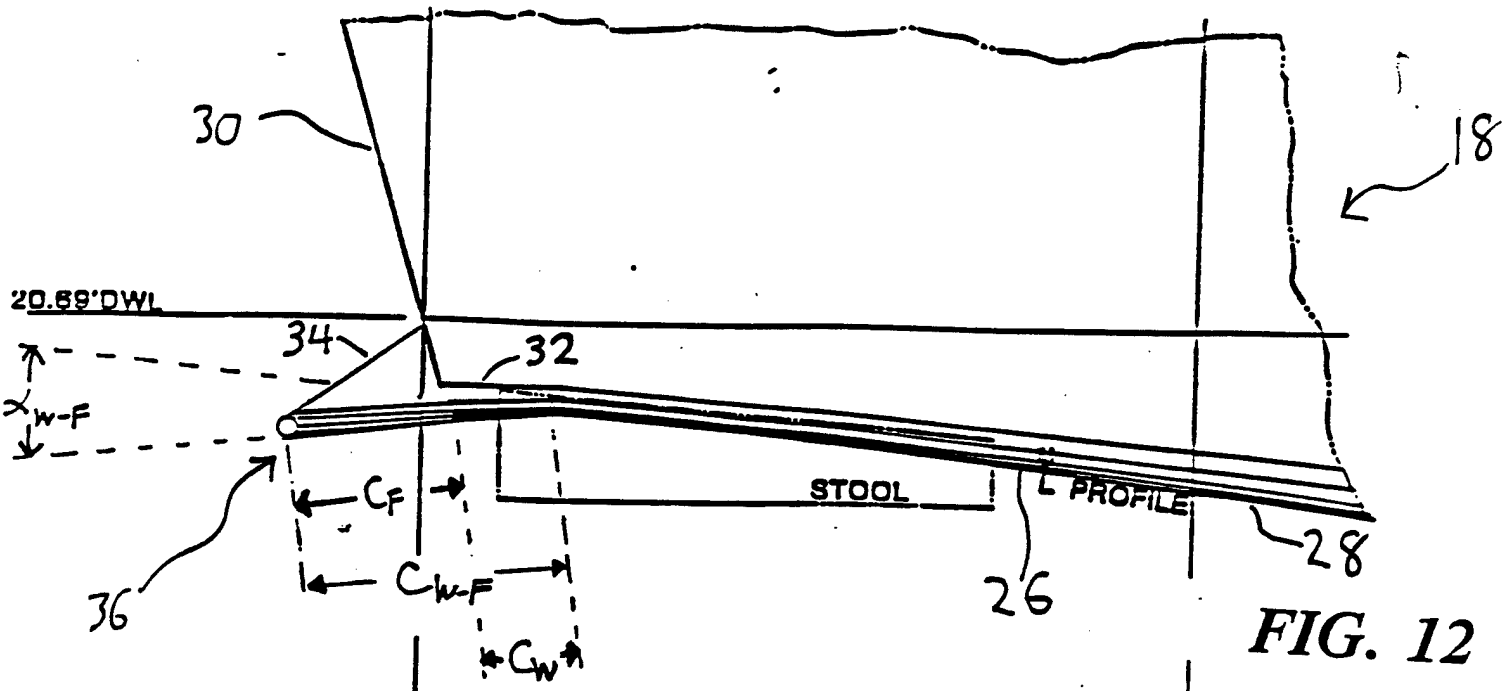
30
18
20.69'DWL
34
32
x_{W-F}
C_F
STOOL
℄ PROFILE
28
36
C_{W-F}
26
C_W

FIG. 12

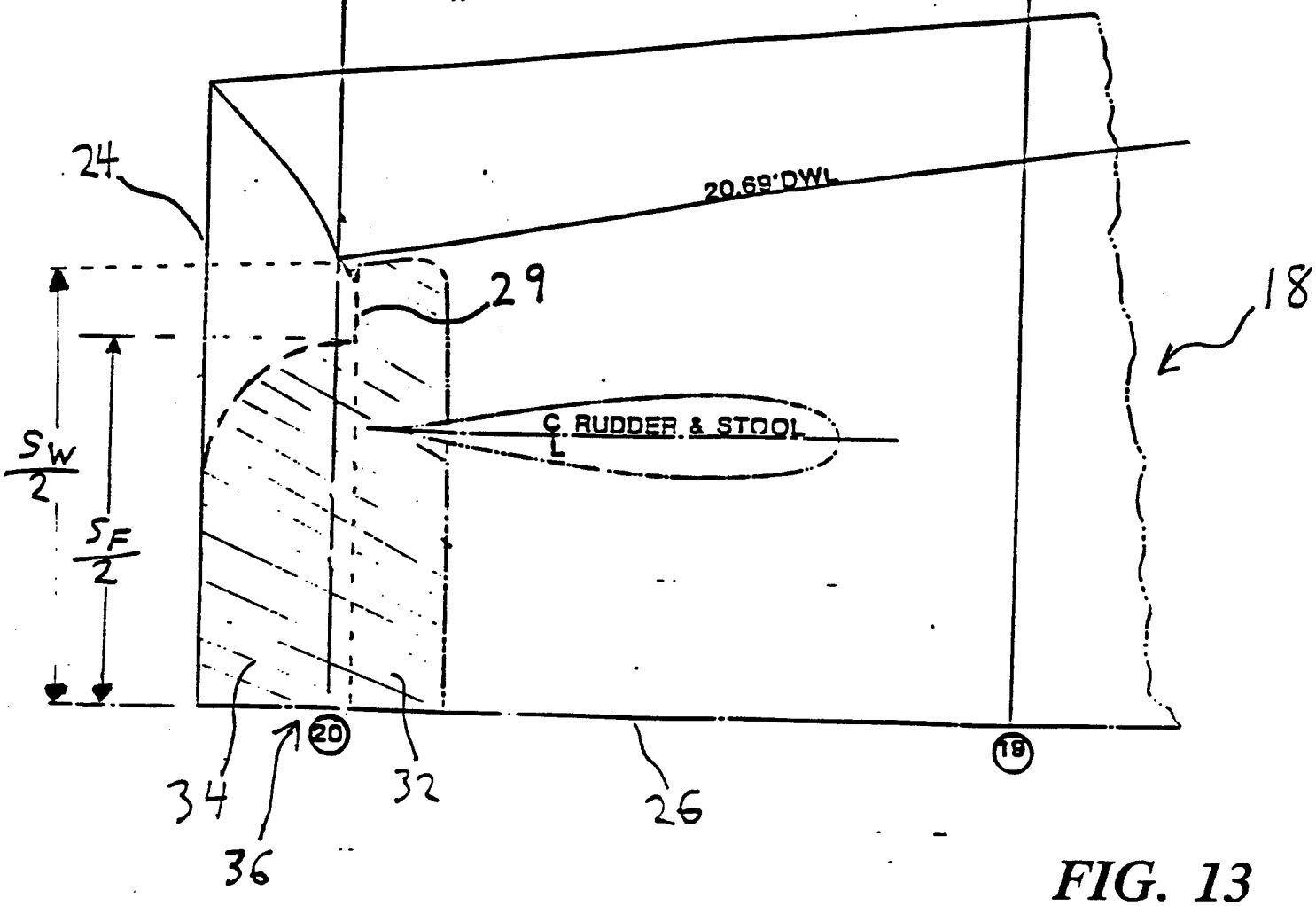
24
20.69'DWL
29
18
℄ RUDDER & STOOL
$\frac{S_W}{2}$
$\frac{S_F}{2}$
20
19
34
32
26
36

FIG. 13