DOLPHIN HYDRODYNAMICS
GRAY'S PARADOX REVISITED

Peter W. Carpenter
University of Warwick, U.K.

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GRAY'S (1936) PARADOX

STUDIES IN ANIMAL LOCOMOTION

VI. THE PROPULSIVE POWERS OF THE DOLPHIN

By J. GRAY

(Sub-Department of Experimental Zoology, Cambridge)

(*Received August* 10, 1935)

(With Three Text-figures)

It is well known that certain aquatic vertebrates (notably dolphins and some of the larger teleostean fishes) are able to travel at surprisingly high speeds. The movements performed by such animals during rectilinear locomotion are all of the same ... for the ... dy vibrates rhyth... lane at right-...

... in this paper are valid, the narrow peduncle and ... well adapted to a free flow of water from all the posterior regions of the body surface to the trailing surface of the fin.

SUMMARY

1. If the resistance of an actively swimming dolphin is equal to that of a rigid model towed at the same speed, the muscles must be capable of generating energy at a rate at least seven times greater than that of other types of mammalian muscle.

2. Observation of the flow of particles past the surface of models similar in form to a fish or dolphin shows that rhythmical movements, such as are characteristic of the body and caudal fin of the living animals, exert an accelerating effect on the surrounding water in the direction of the posterior end of the model. An effect of this type may be expected to prevent turbulence in the flow of water past the body.

3. If the flow of water past the body of a dolphin is free from turbulence, the horse-power developed per pound of muscle agrees closely with that of other types of mammalian muscle.

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GRAY'S PARADOX

Following contemporary naval engineering practice Gray (1936) modelled the dolphin body as a flat plate to estimate drag assuming transition occurred at

$$Re_x = 2 \times 10^6$$

POWER = DRAG x SWIMMING SPEED

He found that to swim at 10 m/s the specific muscle power output required was

7 x mammalian norm (of 40 W/kg)

POWER OUTPUT OF MUSCLES

Muscle performance depends on type of fibre

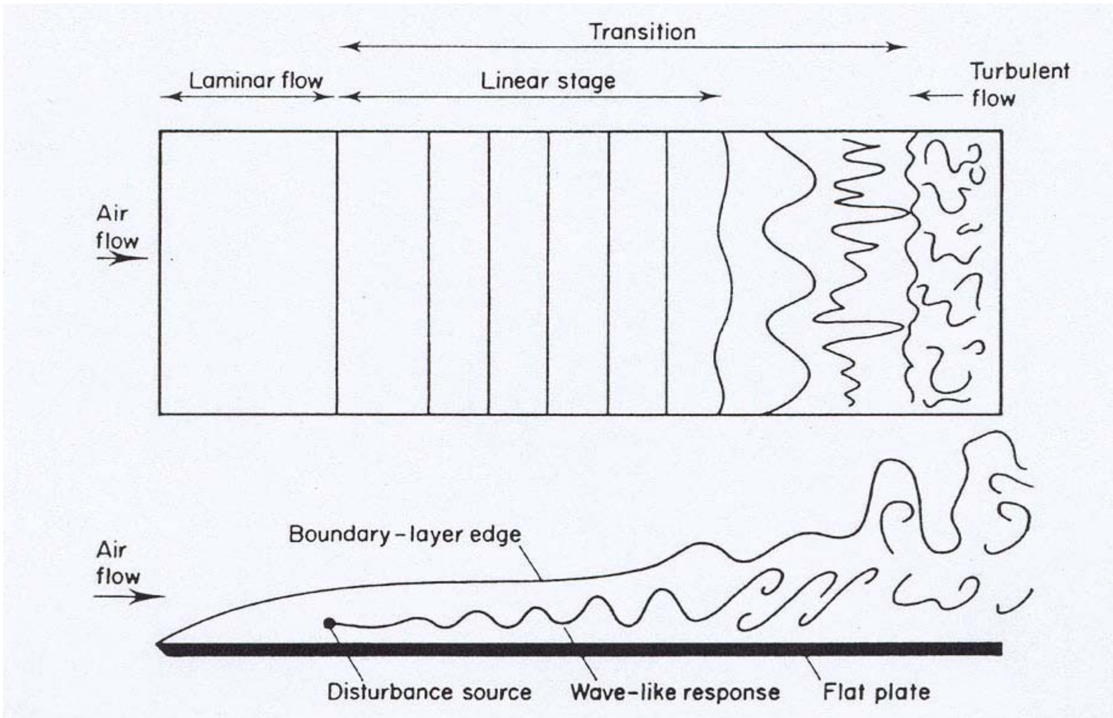
- *Slow oxidative fibres*
  - Mainly aerobic metabolism
  - Slow sustained activity
  - Relatively slow contraction rates
- *Fast glycolic fibres*
  - Mainly anaerobic metabolism
  - Short-burst activity
  - High power output
  - Very high intrinsic contraction speeds
  - Power output is 2 to 17 times that of slow fibres

Dolphin muscle has both types of fibre
Sustained aerobic output = **40 W/kg** (Parry 1949)
Short-duration anaerobic output = **110 W/kg**
(Weis-Fogh & Alexander 1977)

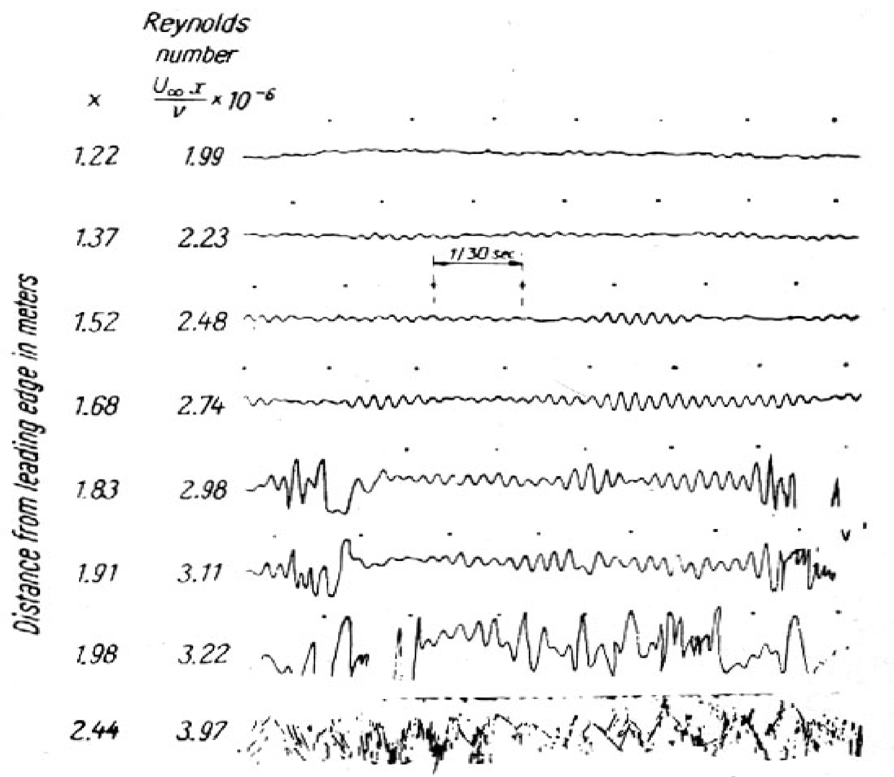
IMPROVED ESTIMATE OF TRANSITIONAL REYNOLDS NUMBER

Gray’s approach reasonably sound except for value assumed for transitional Re.

PHYSICS OF TRANSITION

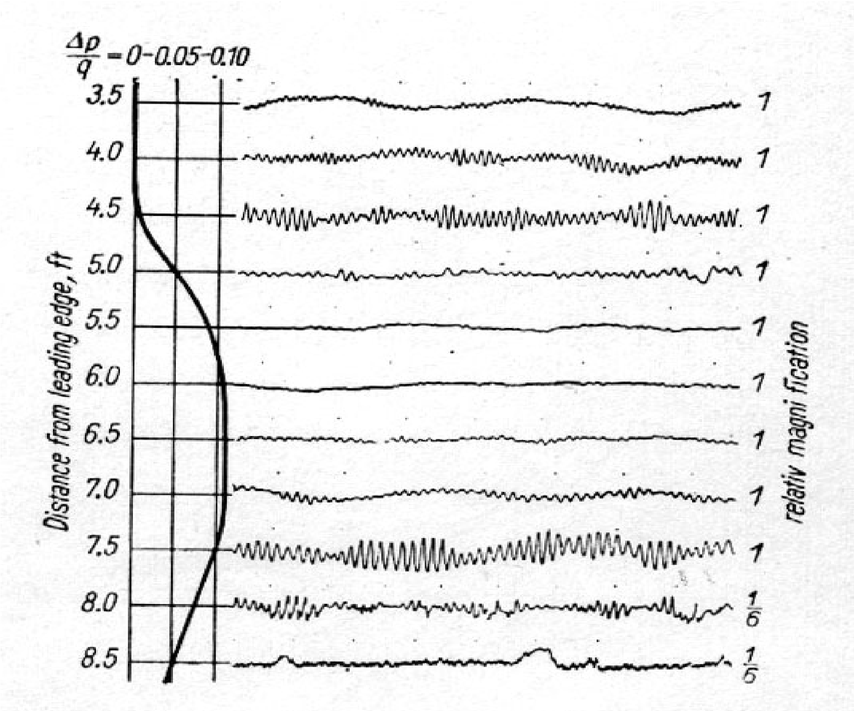


Tollmien-Schlichting waves in natural transition



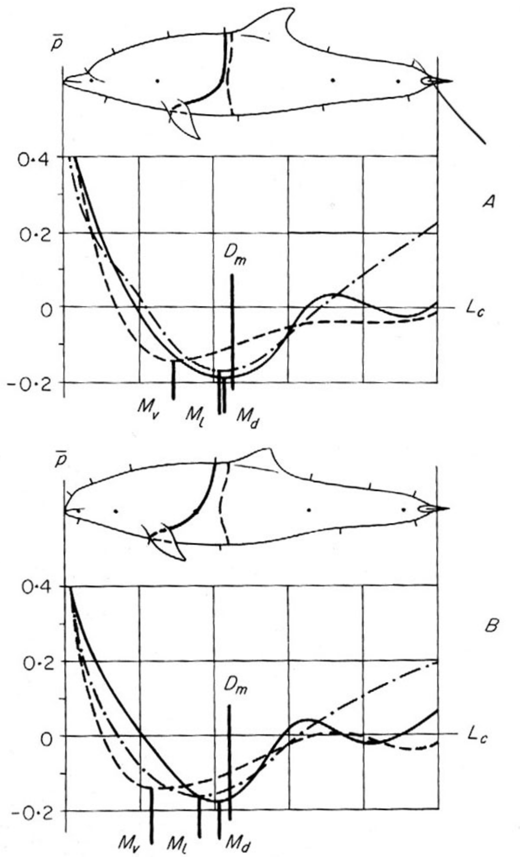
Schubauer & Skramstadt (1947)

Effect of streamwise pressure gradient on growth of T/S waves



Schubauer & Skramstadt (1947)

Streamwise pressure distribution along dolphin body



From Aleev (1977)

$Re_t = 0.5 \times Re_L$

i.e. about 10,000,000 for a

2 m long dolphin swimming at

10 m/s

DRAG COEFFICIENTS: DOLPHINS & RELATED BODIES

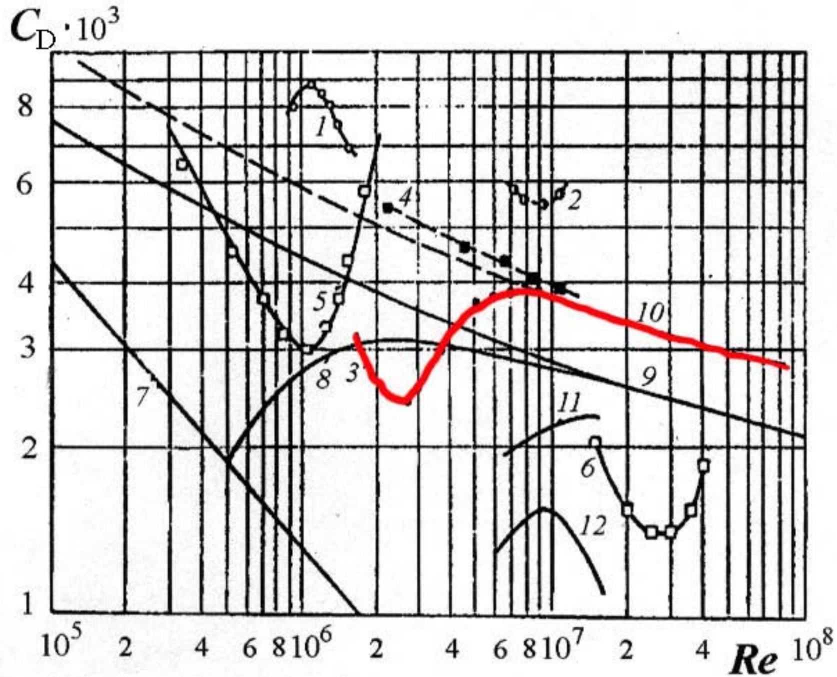


Fig. 7 of Babenko & Carpenter (2002)

1, dolphin C_D due to Kayan (1979) theory; 2, dolphin C_D during braking
3. During inertial swimming; 4, computed C_D for equivalent rigid body
5, dead dolphin; 6, model with artificial dolphin skin; 7,8,9 rigid flat plate
with laminar, transitional & turbulent flow; 11, 12 Kramer's experiments.

New estimates of swimming speed in m/s

Case	C_D	Sustained Power output (40W/kg)	Maximum 110 W/kg
$Re_t = 2 \times 10^6$ Gray	0.0025	5.6	7.9
$Re_t = 13.75 \times 10^6$	0.0015	6.6	9.3
Laminar	0.00025	12.08	16.9
Gliding dolphin	0.0023	6.5	9.0

DATA FOR SUSTAINED SWIMMING SPEED

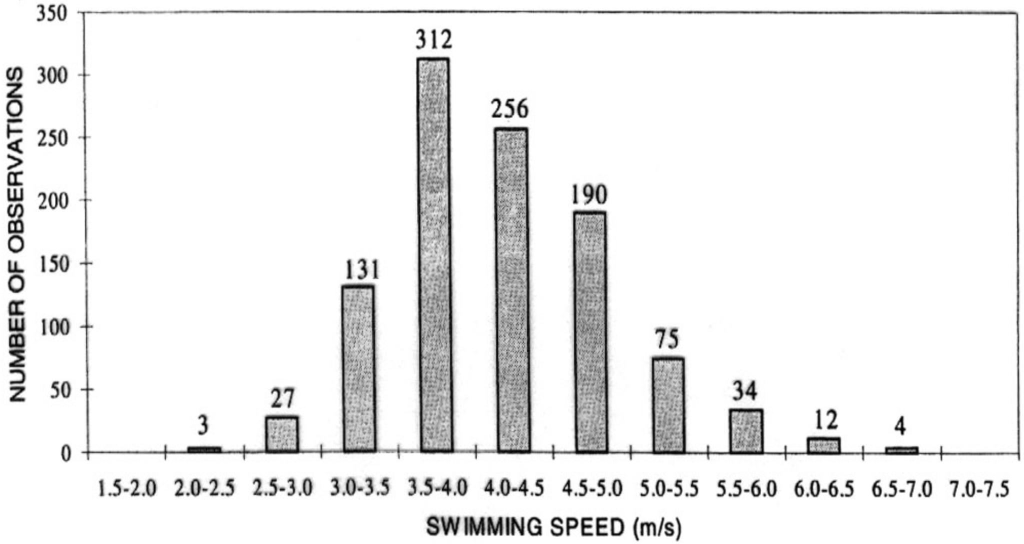
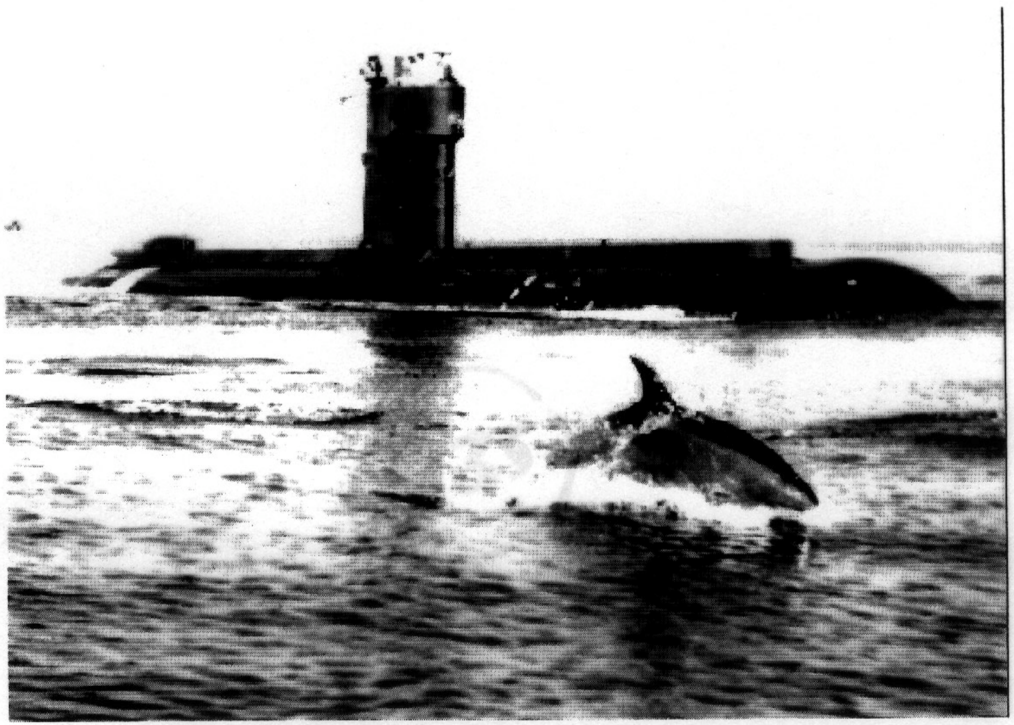
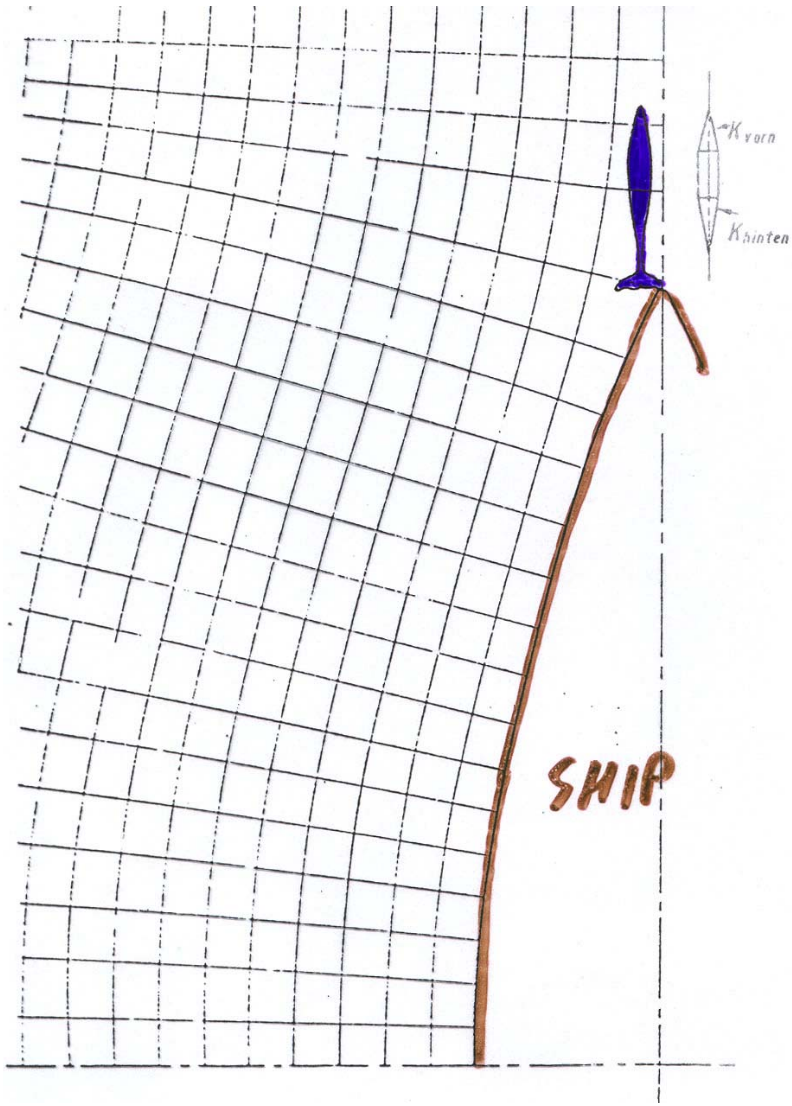


Figure 6. Total distribution of swimming speeds (m/s) obtained from five airplane passes over a school of long-beaked, common dolphins (*Delphinus capensis*); total number of observations equals 1044 (from Rohr et al., 1998b)

Most reliable aircraft-based observations of a school of common dolphins.

MOST EARLIER OBSERVATIONS WERE FROM SHIPS





EXPLOITING SHIP'S PRESSURE FIELD

Focke (1965)

At high speed the mode of swimming comprises alternate leaps and submerged swimming

Assuming exit angle of 30 degrees & minimum feasible leap height of 0.5 m, equating potential & kinetic energy gives 3.6 m/s as onset speed for ‘porpoisIng’. This is consistent with observation.

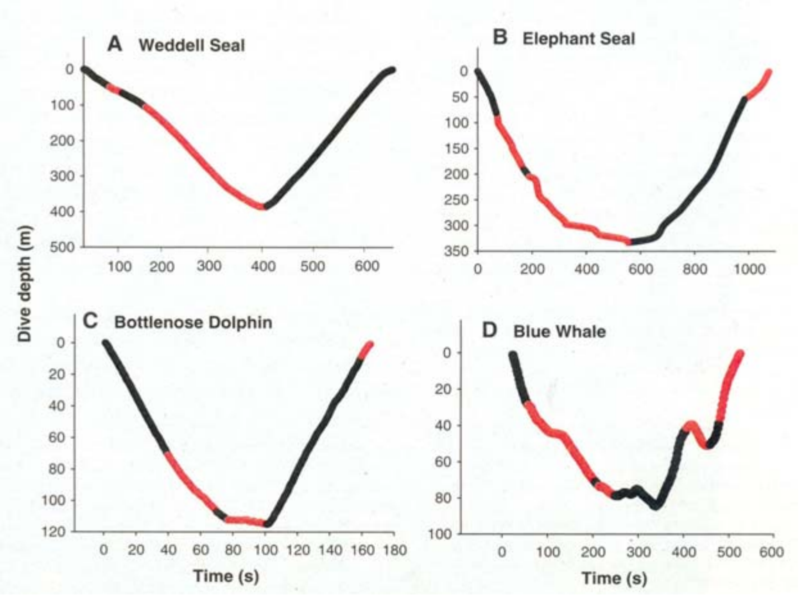
DOLPHIN'S NEED FOR LAMINAR-FLOW CONTROL

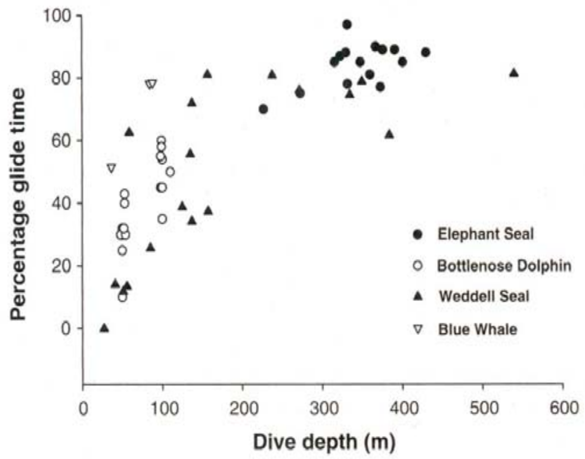
- Most scientists have followed Gray and focussed on maximum sustained swimming speed.
- Laminar flow needed to reach 10 m/s but not to reach commonly observed speeds. In any case the 'porpoising' swimming mode is used at high speeds
- Laminar-flow control more likely required for conserving energy during:

  Slower long-duration swimming

  Deep diving

ENERGY-EFFICIENT DEEP DIVING





Red: gliding; Black: powered swimming

Figs. From Williams *et al.* (2000) *Science* **288,** 133-136

DIRECT EVIDENCE OF LAMINAR FLOW OVER DOLPHIN BODY

1) *Hot-film & pressure-sensor measurements*

Kozlov *et al. (1974), Kozlov & Shakalo, Pyatetskii* et al. (1982), Romanenko (1986)

Overall conclusion is that fluctuation level in boundary layer over dolphin is much lower than comparable rigid body.

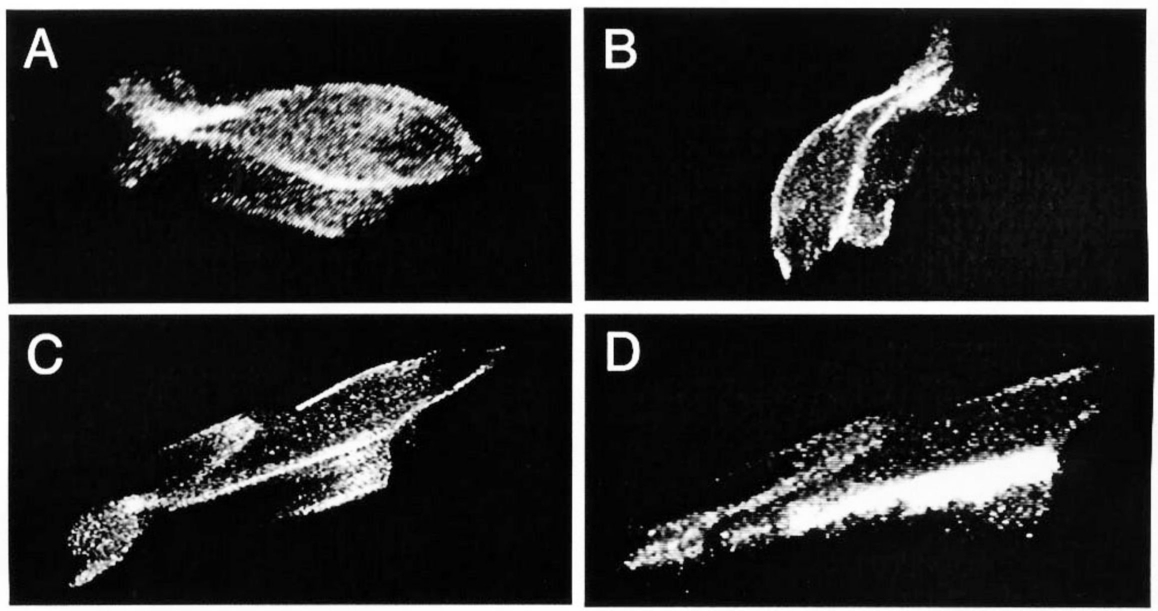
2) Bioluminescence

Much anecdotal evidence. For hard evidence see

Rohr *et al.* (1998) *J. Exp. Biol.* **201**, 1127-60.

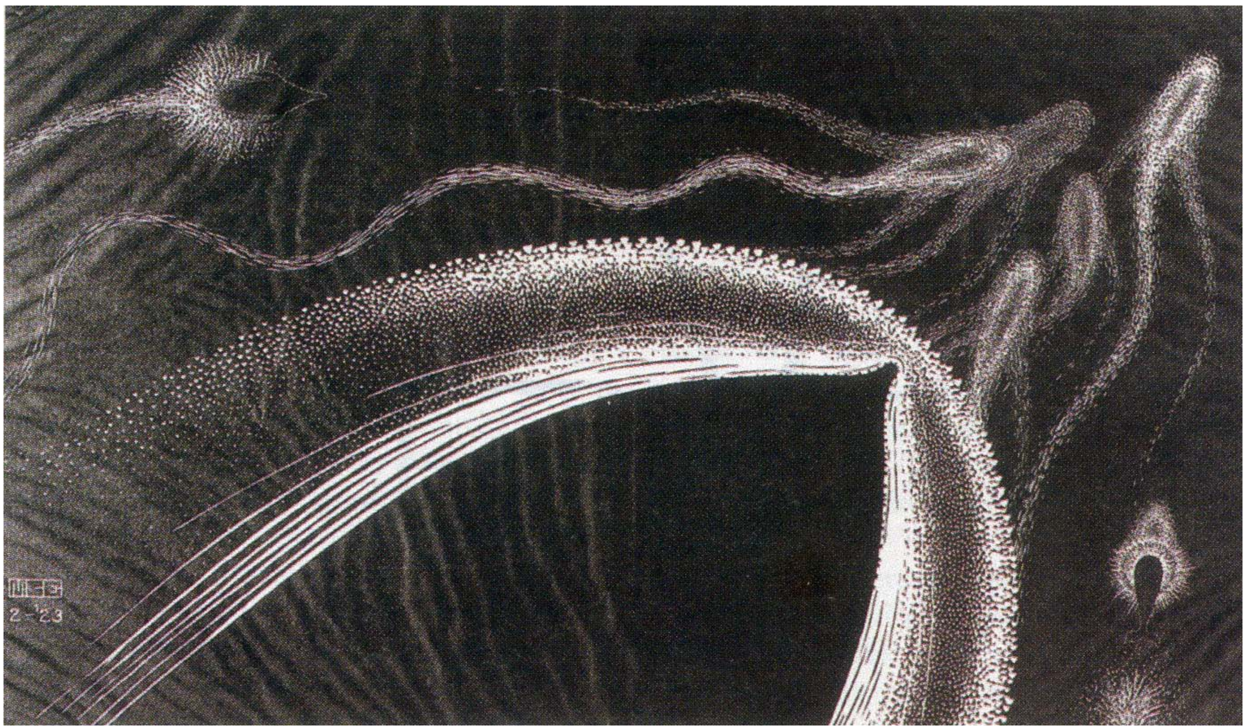
Herring (1998) *Nature* **393**, 731-732.

DOLPHINS & BIOLUMINESCENCE

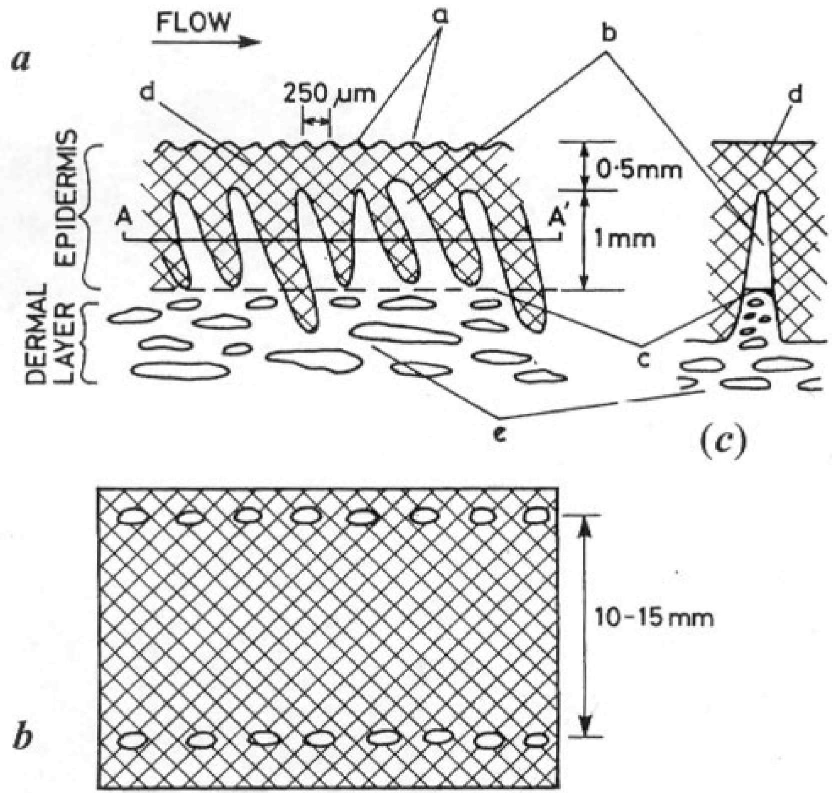


From Rohr *et al. (1998)*

AN ARTIST’S IMPRESSION
Escher (1924)



STRUCTURE OF DOLPHIN'S EPIDERMIS



Figs. (a): Longitudinal cross-section; (b) horizontal section through AA';
(c); Lateral cross-section.

Key: *a,* cutaneous ridges (or microscales); *b*, dermal papillae; *c,* dermal ridge; *d,* upper epidermal layer; *e,* fatty tissue.

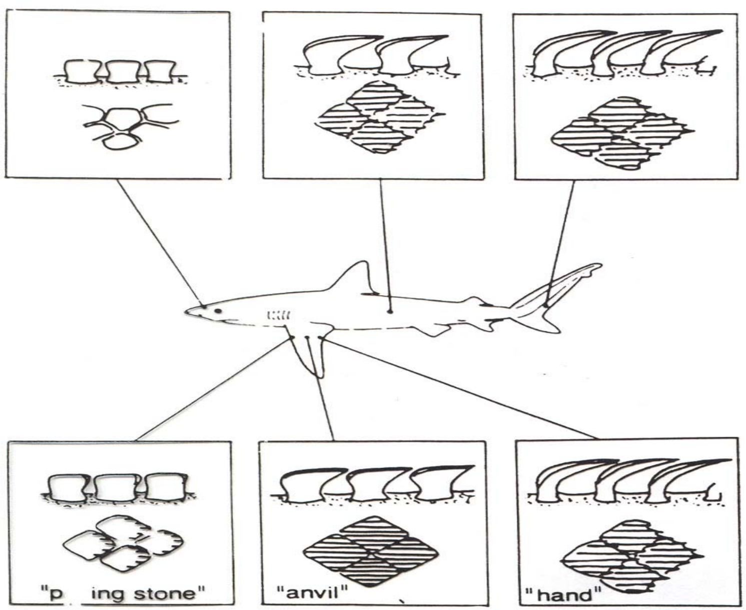
From Carpenter *et al.* (2000) *Current Science* **79**,758-765

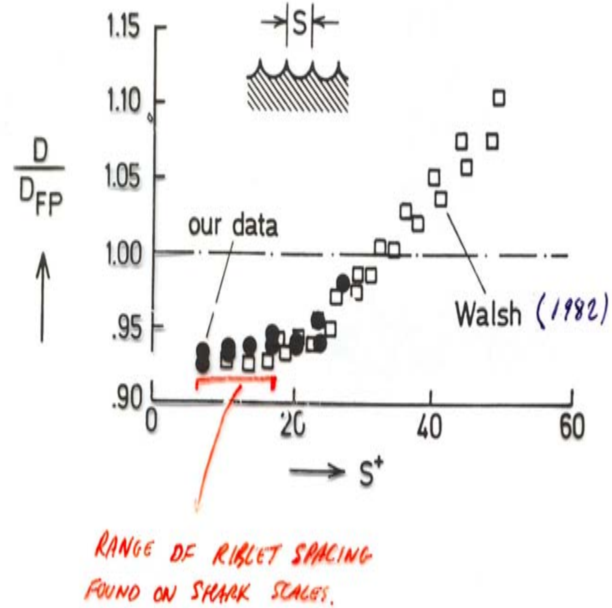
TWO FEATURES OF HYDRODYNAMIC SIGNIFICANCE

1) *Dermal ridges*
These run in streamwise direction
cf shark scales and riblets

2) *Cutaneous ridges*
These run normal to flow direction.

SHARK SCALES & RIBLETS



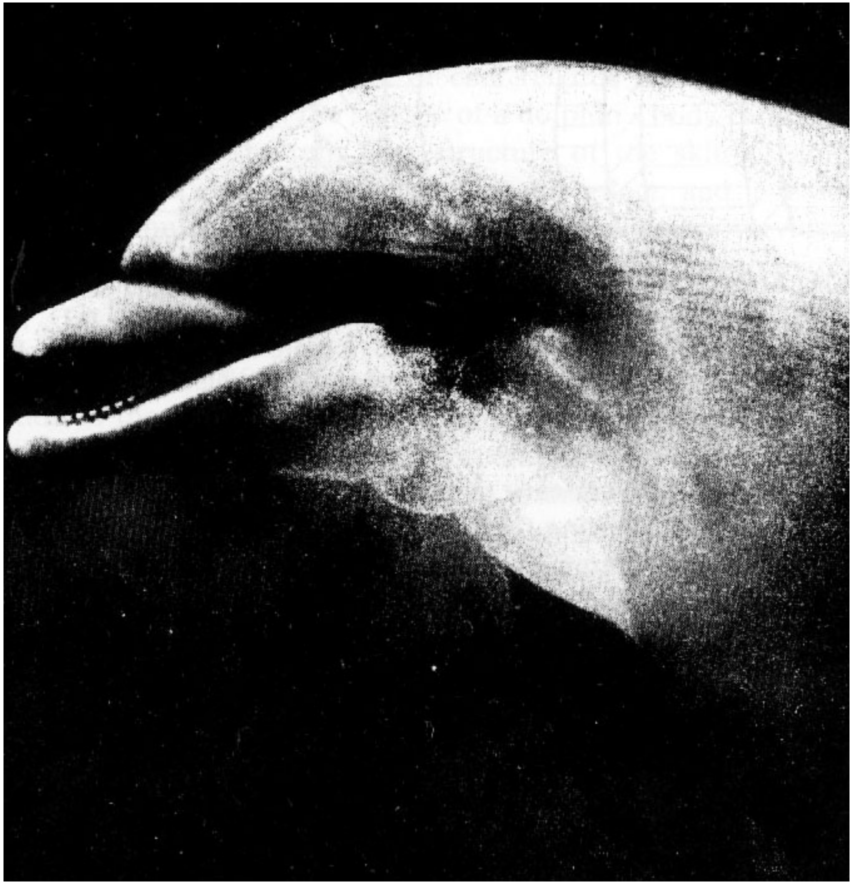


Lateral spacing between ridges on shark scales is ca. 50 μm. Riblets are only effective for turbulent flow.

DERMAL RIDGES

Lateral spacing is ca. 10-15 mm.

Therefore not adapted as riblets for turbulent flow.



CUTANEOUS RIDGES

Aligned normal to the streamwise direction

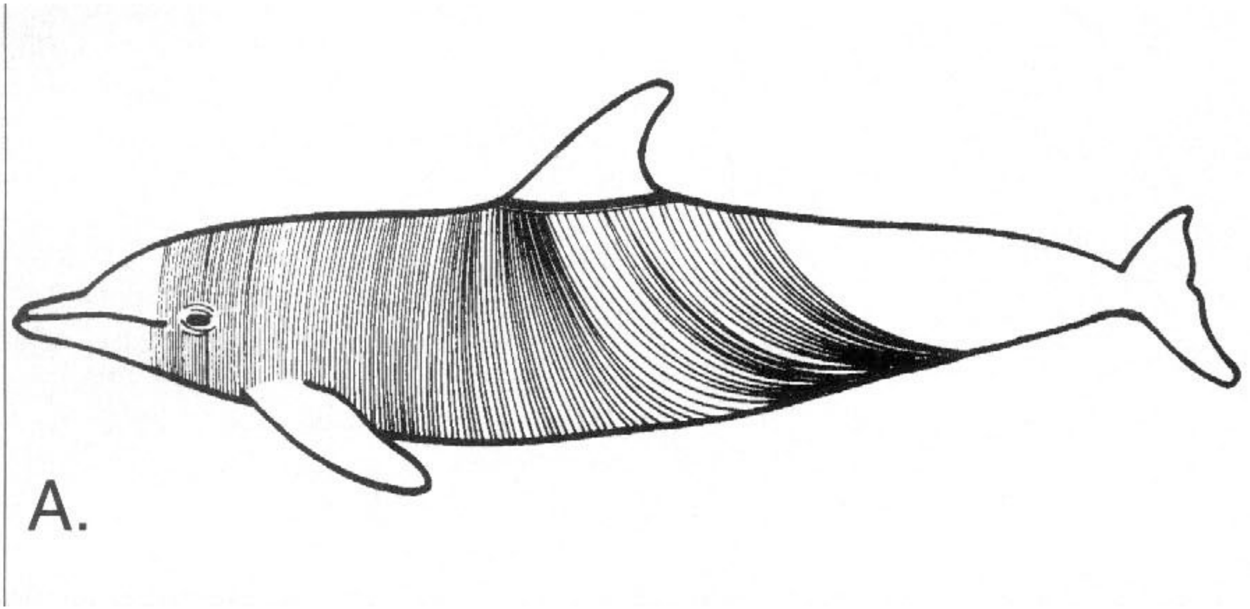
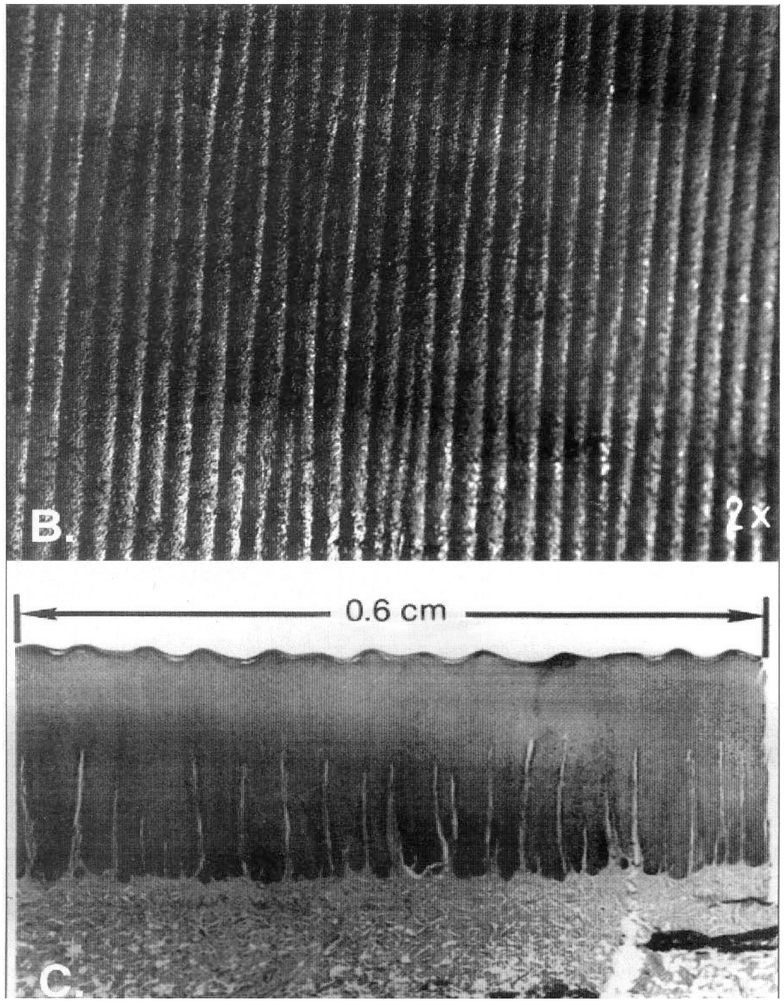


Fig from Ridgway & Carder (1993) *IEEE Eng. Med. Biol.* **12**, 83-88

CUTANEOUS RIDGES
Ridgway & Carder(1993)

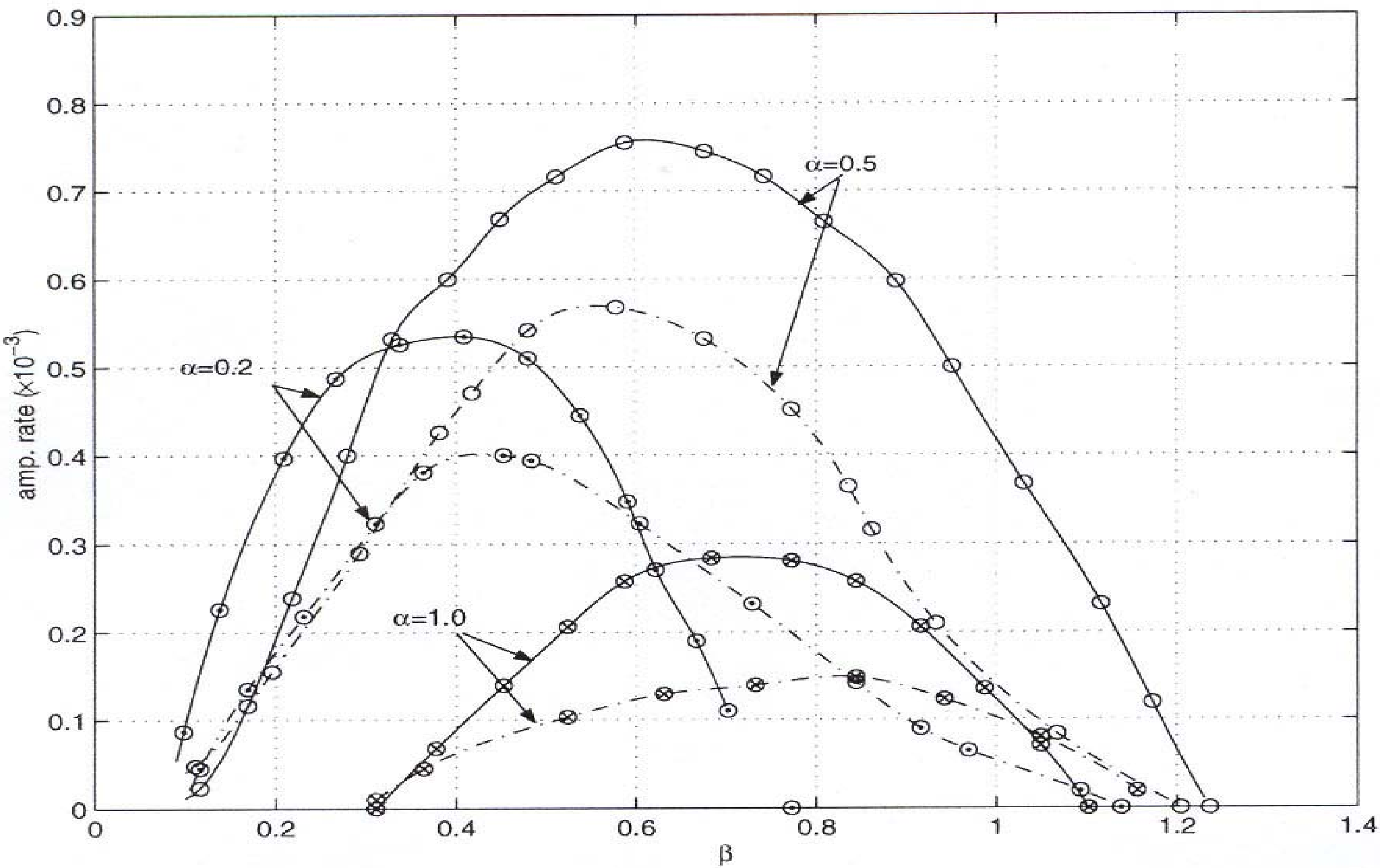


HYDRODYNAMIC FUNCTION OF CUTANEOUS RIDGES

Oblique Tollmien-Schlichting waves grow fastest over compliant walls

Numerical simulation of Ali & Carpenter (2002) show that their growth rate is much reduced when cutaneous ridges are present

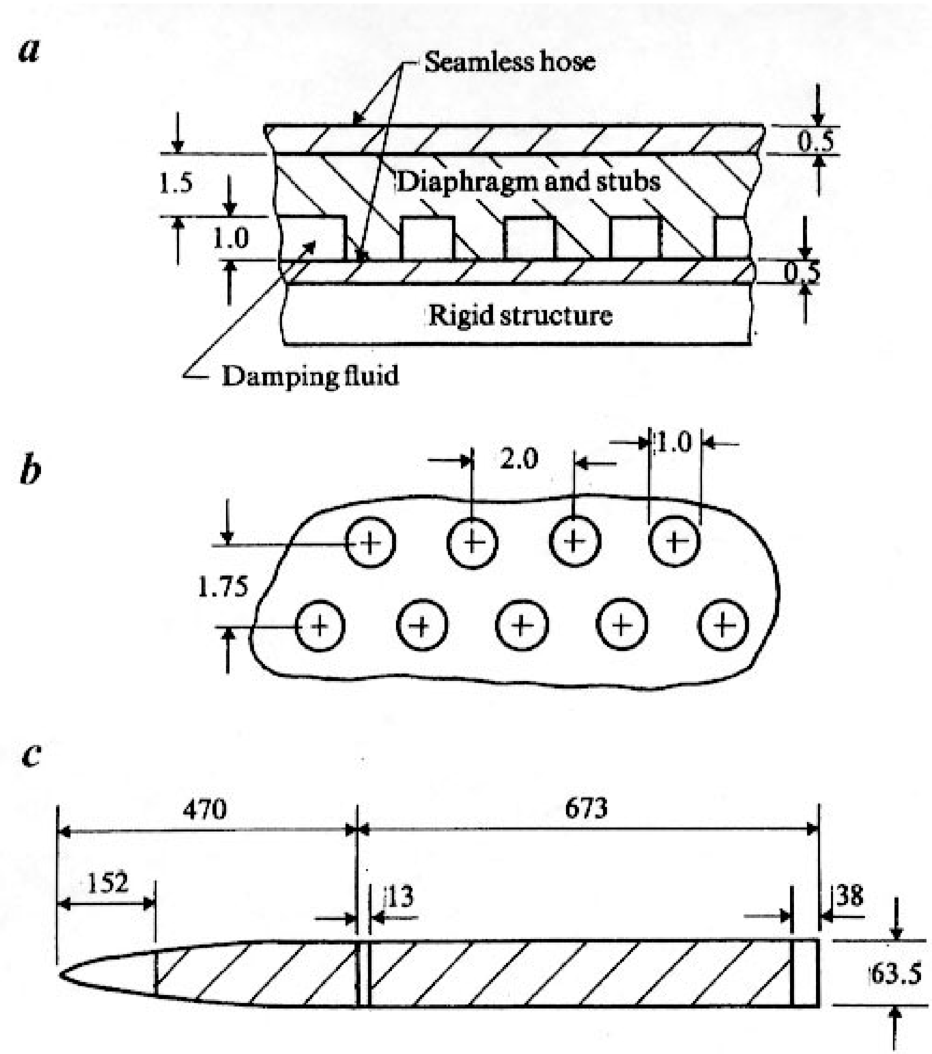
Growth rate vs spanwise wave number
Flow conditions corresponding to dolphin



ARTIFICIAL ANALOGUE DOLPHIN SKINS

Most well-known example is Kramer's (1957, 1960) compliant coating

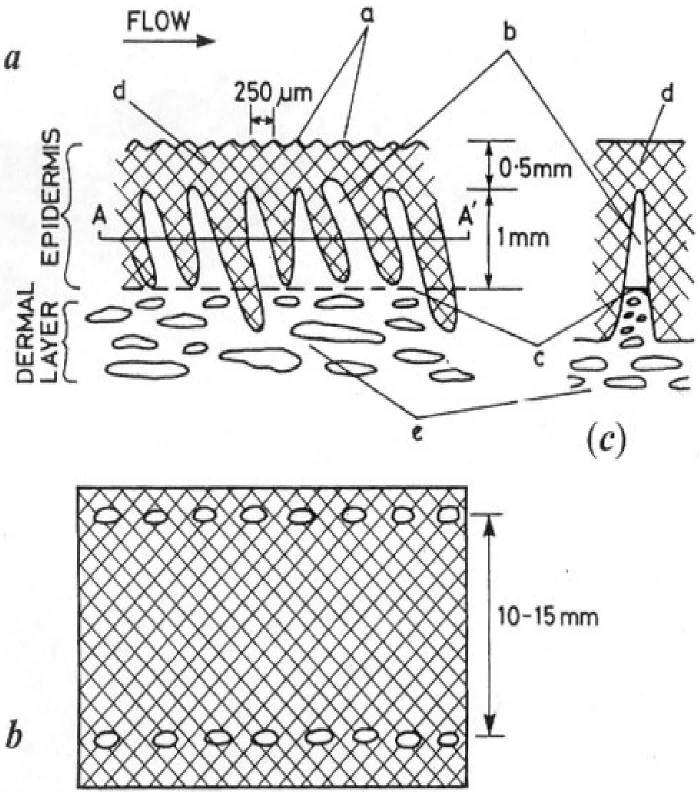
KRAMER COMPLIANT COATINGS



Up to 60 % drag reduction at 18 m/s

Laminar-flow properties confirmed theoretically & experimentally by Carpenter & Garrad (1985, 1986), Gaster (1987) and Lucey & Carpenter (1995)

STRUCTURE OF DOLPHIN'S EPIDERMIS



The angle of inclination of the dermal papillae vary over the body from 10 to 65 degrees relative to surface

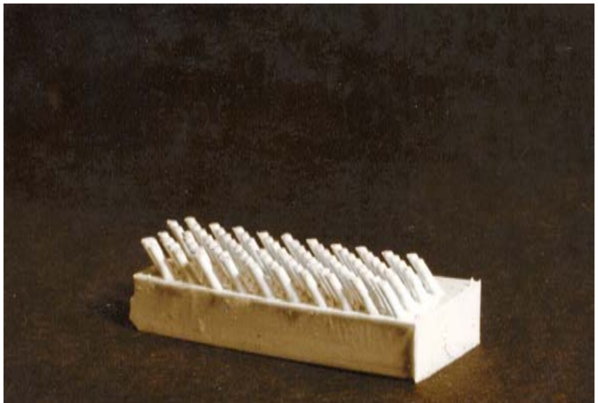
Babenko & Surkina (1969)

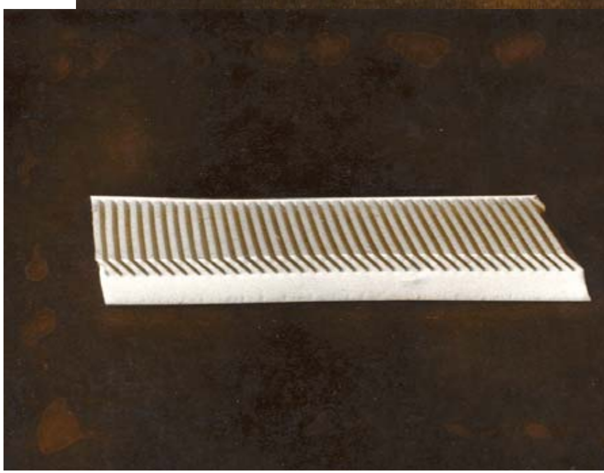
Figs. (a): Longitudinal cross-section; (b) horizontal section through AA';
(c); Lateral cross-section.

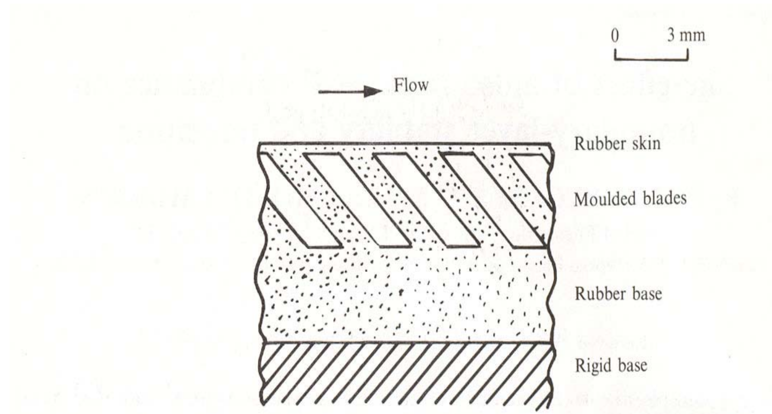
Key: *a,* cutaneous ridges (or microscales); *b*, dermal papillae; *c,* dermal ridge; *d,* upper epidermal layer; *e,* fatty tissue.

From Carpenter *et al.* (2000) *Current Science* **79**,758-765

GROSSKREUTZ (1971) ANALOGUE DOLPHIN SKIN







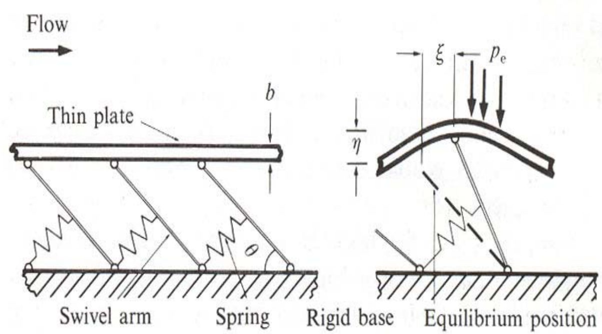


FIGURE 2. Schematic sketch of a simple surface-based theoretical model of an anisotropic compliant wall.

Theoretical modelling due to
Carpenter & Morris (1990) *JFM* **218**,171-223

SURFACE WAVE SPEEDS OF OPTIMIZED COMPLIANT COATINGS

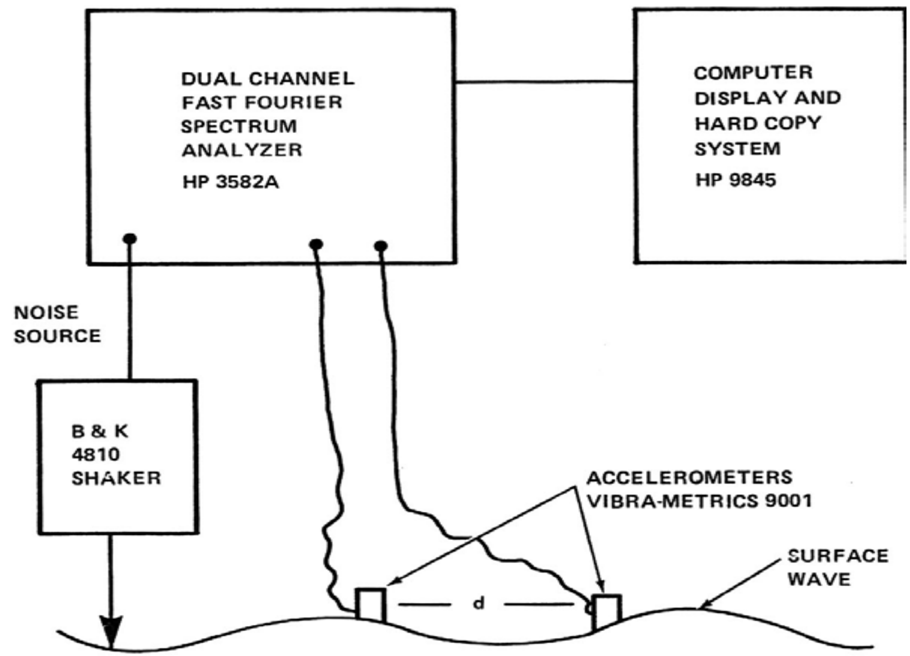
Design methodology developed by
Carpenter & Morris (1990) *JFM* **218**, 171
Dixon, Lucey & Carpenter (1994) *AIAA J* **32**, 256
and others indicate that for compliant coatings optimized for transition delay

Surface-wave speed = 0.7 x Flow speed

Surface-wave speed can be measured on a dolphin and compared with above result.

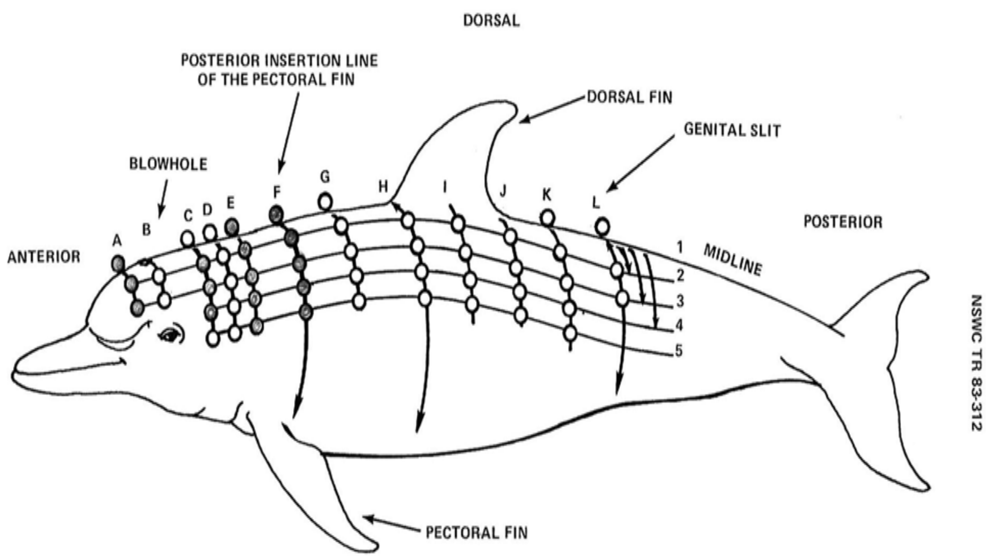
MEASUREMENT OF SURFACE-WAVE SPEED ON DOLPHIN

Madigosky *et al.* (1986) *JASA* **79**, 153-159



Locations of wave-speed measurements

Grey circles: 6-7 m/s; Open circles: no measurement implies dolphin skin optimized for ca. 9 m/s



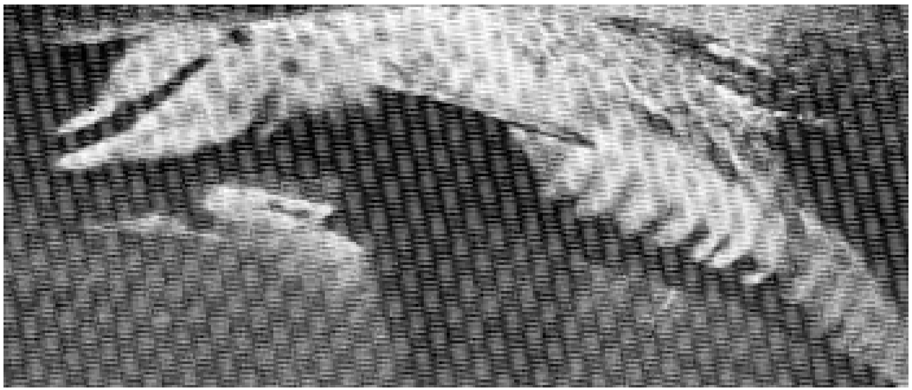
CROSS-SECTIONAL LINES ARE NOTED BY LETTERS

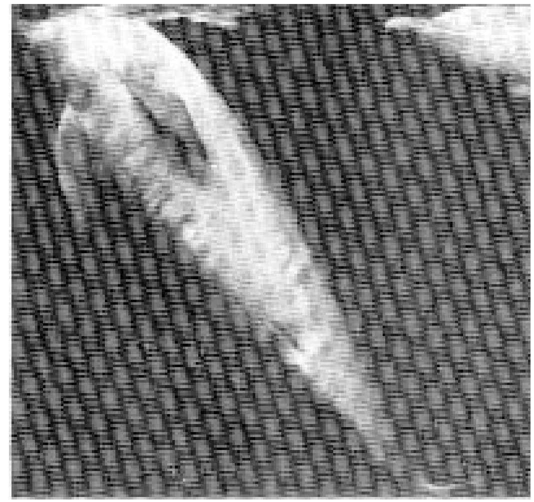
LONGITUDINAL LINES ARE NOTED BY NUMBERS STARTING WITH 1 AT THE MIDLINE

LONGITUDINAL LINES ARE 6 CM APART

O - ACCELEROMETER MIDPOINTS

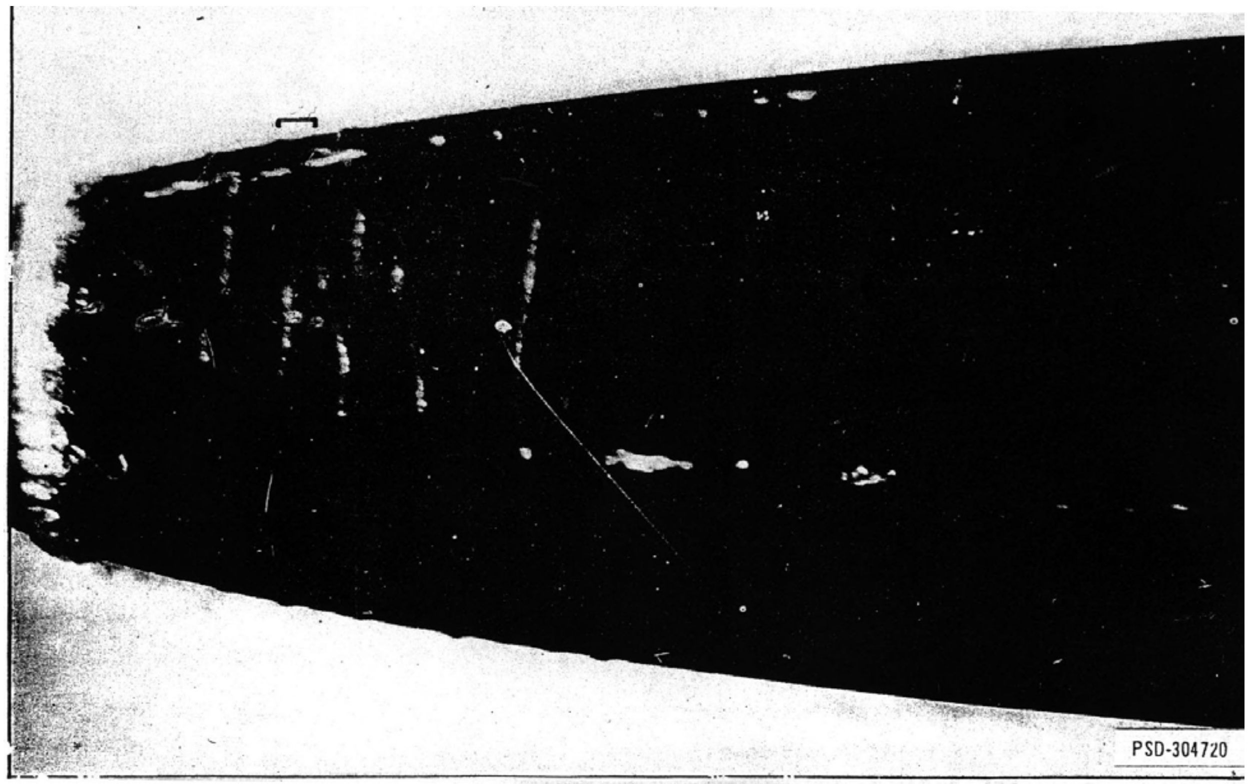
SKIN-FOLDING – HYDROELASTIC INSTABILITY





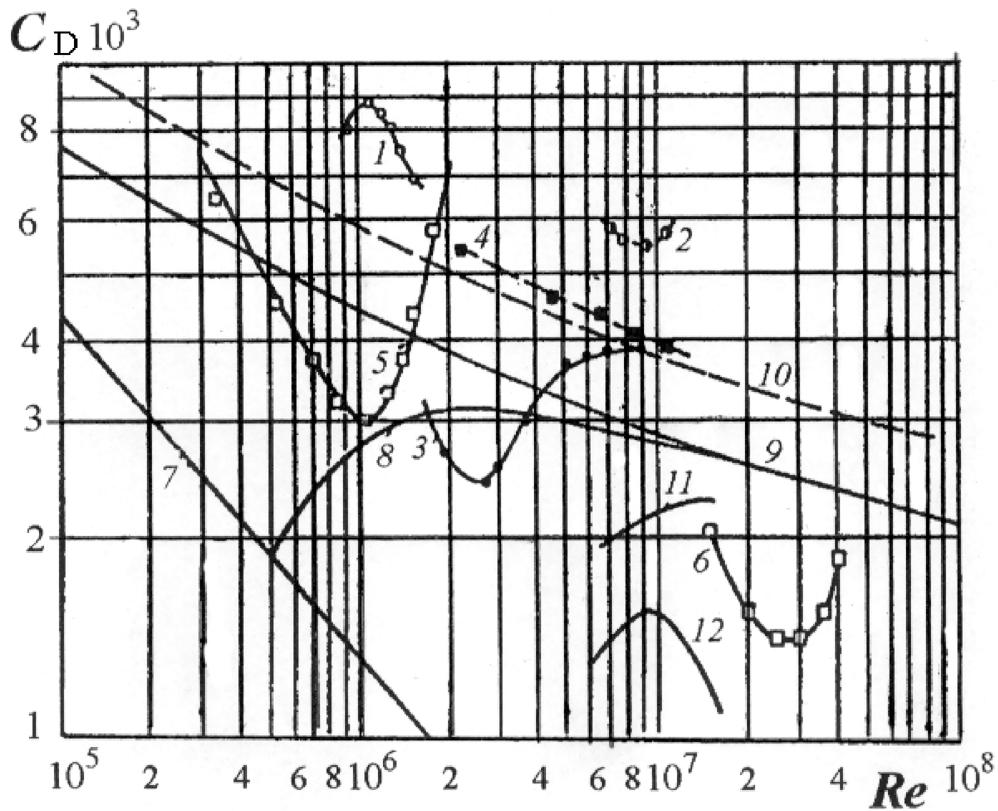
Essapian (1955)*Breviora Mus. Comp. Zool.* **43**, 1-4

Divergence hydroelastic instability on Kramer coating Puryear (1962)



DRAG COEFFICIENTS vs Re_L

Note all analogue & real dolphin curves exhibit a minimum implying a critical onset speed



CONCLUSIONS

1. Dolphins have adequate muscle power for observed sustained swimming speeds.

2. Laminar flow is needed to swim at speeds greater than 7 m/s and may be advantageous for conserving energy during deep diving and at lower swimming speeds.

3. There is direct and indirect evidence of a laminar-flow capability.

4. But multi-facetted & multidisciplinary problem with many unanswered questions.

DOES THE DOLPHIN HAVE A SECRET?