Relaminarization using stationary vortices

OR Dawson, M Bauer, GJ Balle, RE Breidenthal

Abstract

Flow visualization and hot film experiments reveal that an initially turbulent boundary layer is relaminarized over about half the wall surface if stationary, streamwise vortices are introduced into the flow. The geometry is a sinusoidal wall oriented in the essentially the streamwise direction, with a vane-type vortex generator at the upstream end of each trough. Stabilized by the wavy wall, the vortices are positioned in the middle of each trough about even with the crests. A positive pressure gradient in the spanwise direction over half of the wave may account for the residual turbulence. While the wavy wall was initially intended to mimic the dividing streamline of a von Karman wake to achieve vortex stabilization, the observed flow instead resembles Kelvin's cat's eyes flow pattern. This may reflect a more general behavior, since Oster & Wygnanski and Roberts had found that the shear layer also exhibits laminar fluxes when forcing generates Kelvin's cat's eyes.

OR Dawson
Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109
e-mail: ordawson@gmail.com

M Bauer
Institut für Luft- und Raumfahrt, TU Berlin, Marchstraße 12, 10587 Berlin
e-mail: matthias.bauer@ilr.tu-berlin.de

GJ Balle
Auspira Ltd., P.O. Box 28, Tuakau, New Zealand
e-mail: balle@auspira.com

RE Breidenthal (corresponding author)
University of Washington, Box 352400, Seattle, WA 98195-2400
e-mail: breident@aa.washington.edu

1 Introduction

Vortices normally move with respect to nearby surfaces. However, if a vortex can somehow be held stationary, the physics change in a surprising way. This was first recognized with a vertical jet impinging on a stratified surface. Cotel and Breidenthal (1994) found that the entrainment rate across a stratified interface strongly depends on the stationarity of the entraining vortex. In order to test this assertion, Larry Redekopp (personal communication 1995) suggested a new experiment on a precessing jet. Compared to the vertical jet, the entrainment rate from a slightly tilted and precessing jet is *reduced* by orders of magnitude (Cotel et al. 1997), as predicted.

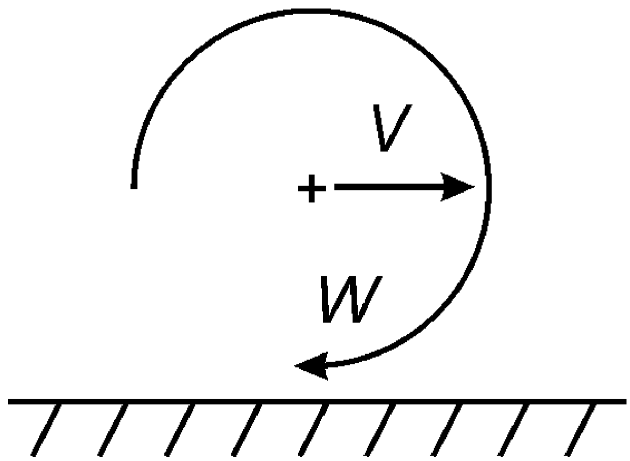

Fig. 1 The intrinsic velocity ratio W/V of a vortex near a surface

In order to account for the observations, a new parameter was proposed. Originally termed the "persistence parameter", it is an intrinsic velocity ratio of an eddy near a surface (Fig. 1). The ratio of the rotational to the translational speed of the vortex with respect to the surface is a measure of the vortex stationarity. If this ratio becomes large compared to one, the vortex is sufficiently stationary to be "persistent". We have discovered that physics is completely different from the other, non-stationary limit.

If correct, the concept should also apply when the surface is an iso-vorticity surface of a neighboring vortex. Gharib (personal communication 1995) has noted that this intrinsic velocity ratio is essentially equivalent to the formation number of starting jets (Gharib et al. 1998).

That surface can also be a solid wall. In order to test this hypothesis in the stationary limit, it is first necessary to achieve a stationary vortex near a wall. However, if the wall is flat, Crow (1970) and Widnall (Widnall et al. 1974) instabilities from the image vortex cause the vortex to oscillate, destroying the stationarity. Recognizing that the vortices in a von Karman wake are at least quasi-stable, Balle (Balle and Breidenthal 2002) suggested that a wavy surface replacing the dividing streamline of a wake could help stabilize the vortices.

Fig. 2 shows the temporal wake flow. Because of the induced velocity of the vortex array, the wall must be yawed a small angle to maintain the vortices at the sweet spot where they are stationary, as shown in Fig. 3.

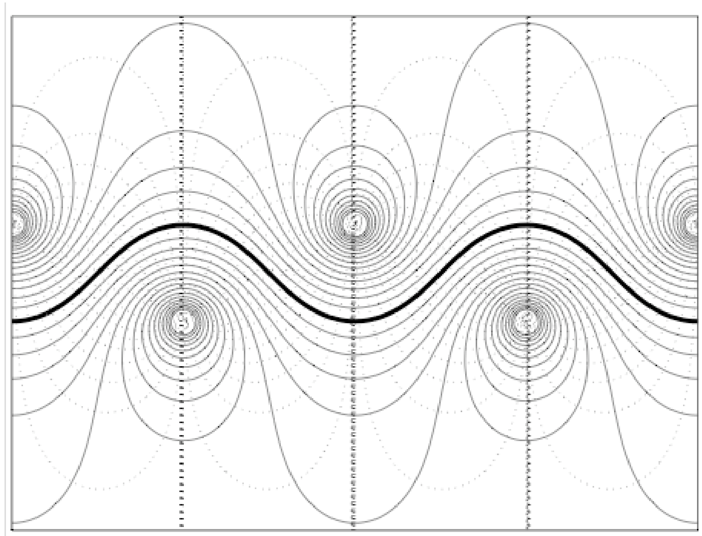

Fig. 2 The von Karman wake, with the dividing streamline in bold

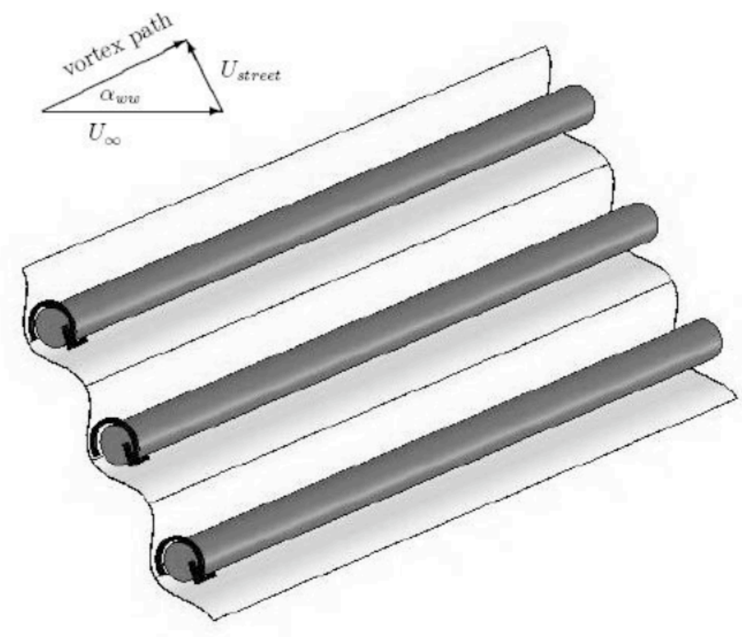

Fig. 3 The wavy wall is yawed slightly (exaggerated here for clarity) to account for the induced crossflow velocity of the vortex array (Dawson 2005)

2 Experiments

All experiments were conducted with thin boundary layers in comparison to the wavelength of the wall. Balle had earlier found that local heat transfer at the bottom of the trough was reduced to laminar values when the vortex was stationary. At a moderate Reynolds number of about 10^5 based on x, the dimensionless heat flux declined by a factor of two compared to the turbulent case. The contrast increased with increasing Reynolds number, going as about $Re^{1/4}$. In short, the heat transfer measurements indicated that the flow was laminar at the bottom of the trough.

Flow visualization by Dawson (2005) and hot film measurements by Bauer (2006) using a larger wavy wall (Fig. 4 and 5) revealed that the flow is laminar over about half of the entire surface, even when the upstream boundary layer is turbulent. Fig. 6 illustrates the turbulent intermittency within the boundary layer as a function of spanwise position over one wavelength of the wall. The intermittency is the fraction of the time that the hot-film signal fluctuates rapidly, indicating turbulent flow.

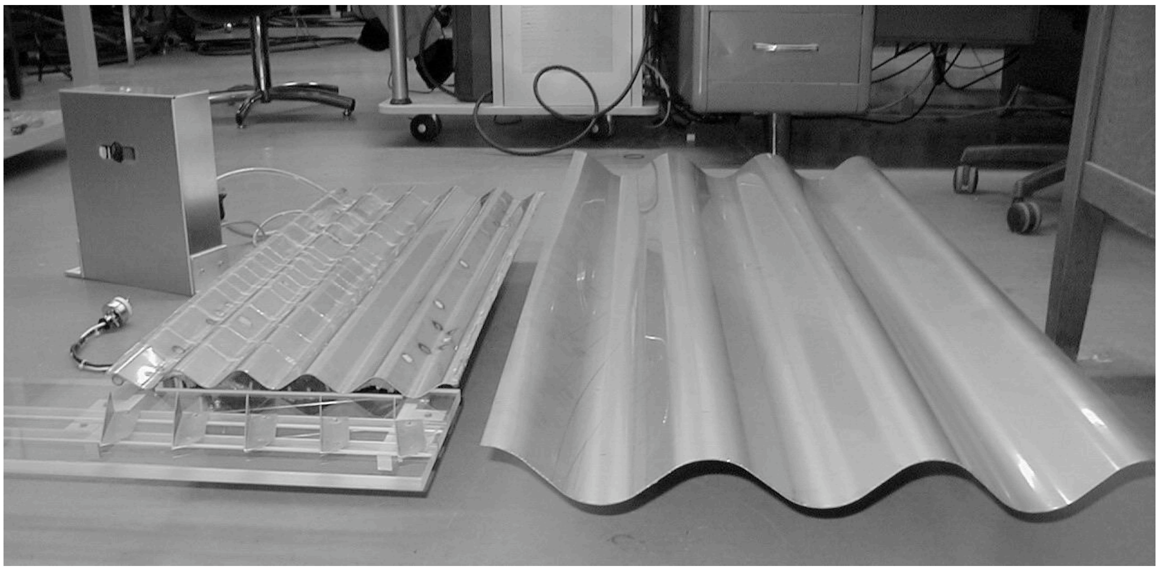

Fig. 4 Small and large wavy walls. With a wavelength of 165 mm, the larger wall allows a higher Reynolds number, up to 60,000 based on wavelength (Dawson 2005).

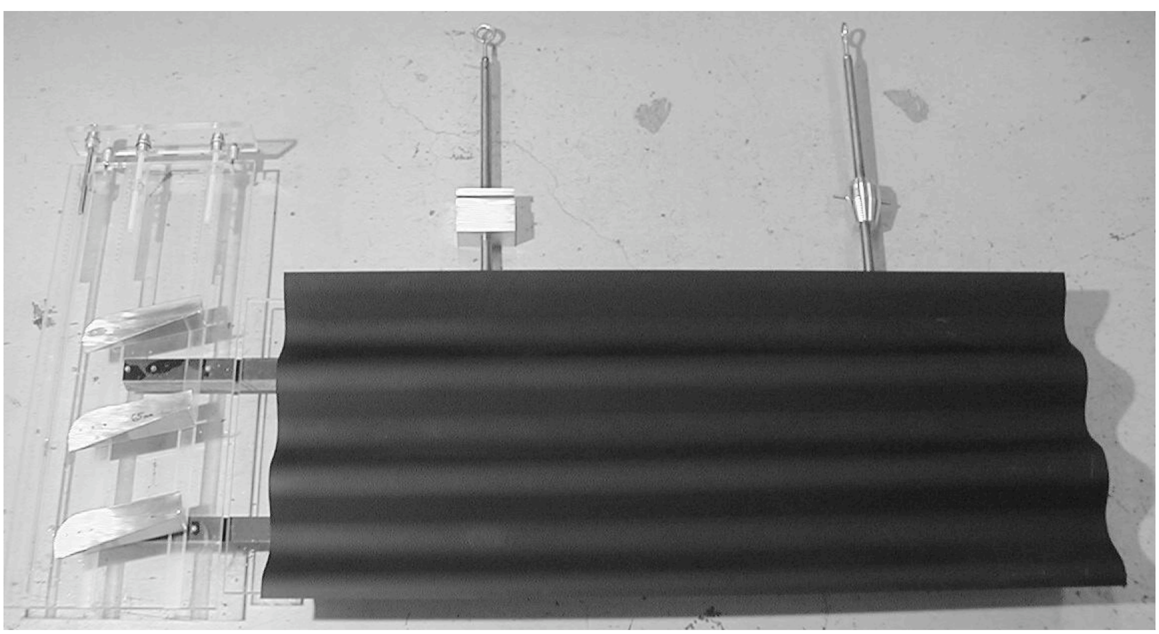

Fig. 5 Large wavy wall painted black, with vortex generators to the left (Dawson 2005)

Similar laminar behavior has been observed in the forced shear layer, where the flow also resembles Kelvin's cat's eyes (Oster and Wygnanski 1982). The Reynolds stresses and entrainment rate become so low that there is no appreciable growth for some interval. Since mixing is entrainment limited, the mixing rate also declines to essentially a laminar value (Roberts and Roshko 1985). Kelvin's cat's eye flow always seems to yield laminar fluxes.

It is counter-intuitive that adding a strong streamwise vortex would reduce the wall fluxes. Indeed, numerous experiments have clearly demonstrated that heat transfer is increased under streamwise vortices (e.g., Eibeck and Eaton 1987). In all of these previous experiments, however, the wall was essentially flat. Consequently, the vortices were not sufficiently stationary and so did not achieve a persistent state. Stationarity makes all the difference.

Other researchers have observed related phenomena. From direct numerical simulations, Schoppa and Hussain (1998) proposed a drag reduction scheme using streamwise vortices in a channel. Fransson et al. (2005) found that Tollmien-Schlichting waves were inhibited by streamwise vortices.

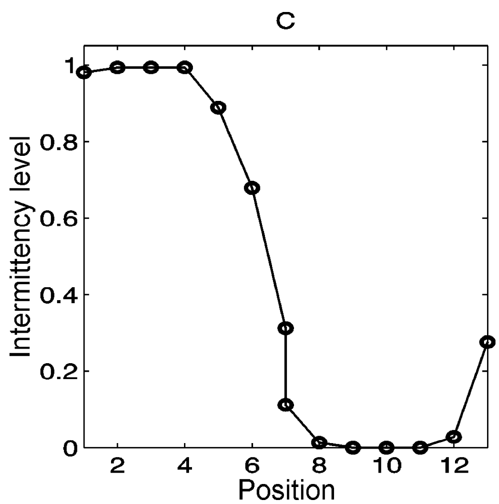

Fig. 6 Turbulent intermittency from crest to crest over one wavelength l at downstream station x/l = 6. Note that the initially turbulent boundary layer is relaminarized over about half the surface (Bauer 2006).

Using dye injection, Dawson sketched the secondary flow pattern (Fig. 7). The pattern is inconsistent with Balle's original concept of a von Karman wake (Fig. 2). Instead, the flow resembles Kelvin's cat's eyes, with a small region of separation near the wave crest (Fig. 8).

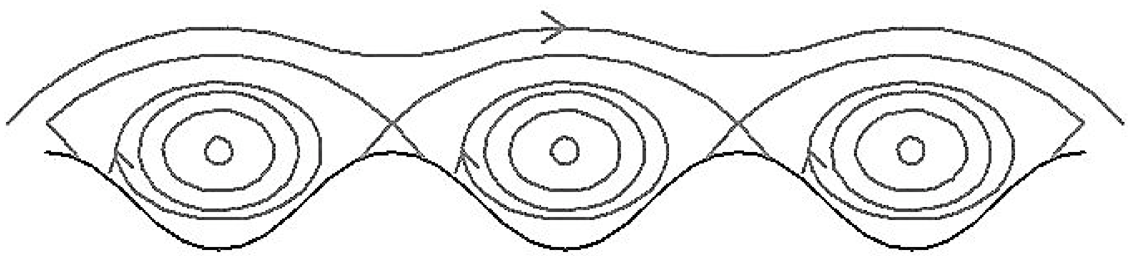

Fig. 7 Sketch of the observed mean streamlines. The boundary layer is laminar between the bottom of each trough and the crest to its right (Dawson 2005)

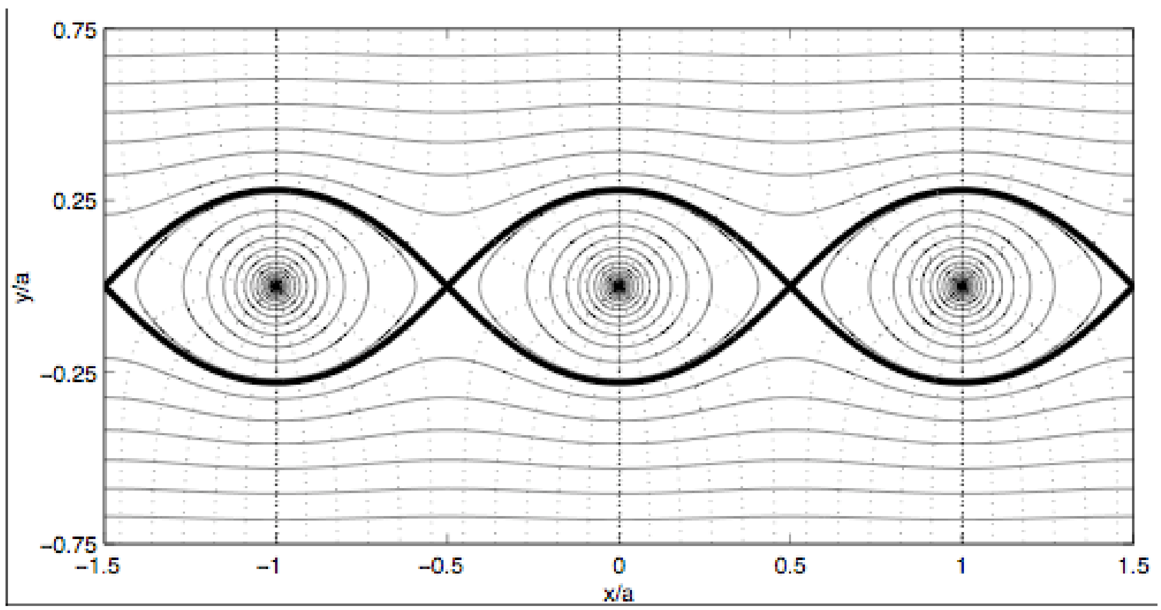

Fig. 8 Kelvin's cat's eye pattern, with the separatrix in bold. Note the resemblance to Figure 7, with the wavy wall approximating the lower separatrix.

While the observed laminar flow is in accord with the basic theoretical concept of vortex persistence, there are several important practical questions that remain open. Can a different wall shape increase the fraction of laminar flow with passive control? Can active control achieve stationary vortices on a flat wall?

Finally, how robust is the relaminarization to freestream turbulence? In order to establish a working hypothesis, one can make a reasonable guess. In a classical turbulent flow, there are only two distinguished eddy sizes: The largest and the smallest. These two eddy sizes each have a characteristic rotational velocity. A reasonable hypothesis is that there is a transition to nonpersistence when the freestream turbulence intensity at the scale of the vortex in question equals the characteristic velocity of the smallest eddy in the corresponding Kolmogorov spectrum. This hypothesis is readily testable by progressively adding freestream turbulence of varying intensity and scale.

3 Potential applications

While a significant reduction in local heat flux at the bottom of the trough has been demonstrated, the wavy wall has a greater wetted area than a flat wall of the same planform. So the total wall heat flux can only be reduced if the laminar flow is sufficiently extensive to compensate for the added surface area as noted by Hans Hornung (personal communication 1999).

Major reductions in heat flux have many attractive applications, such as turbine blade cooling. The thermodynamic efficiency of a turbine engine is severely limited by heat flux to the turbine blades and nozzles.

Another important question is drag reduction. As yet, there are no measurements of skin friction or drag with stationary vortices. The local skin friction is expected to decrease in the laminar zone, of course, but one must pay for the energy invested in the vortex. While it might be possible to recover some fraction of that energy with downstream anti-swirl vanes, it seems probable that appreciable energy must be lost. Therefore a net drag reduction for flow over a flat plate seems unlikely.

However, for a lifting wing operating at a reasonable lift coefficient, the boundary layer typically separates before reaching the trailing edge, causing a thick wake and appreciable drag. Imagine a wing with stationary vortices over most of the upper surface. The skin friction there is reduced. Suppose that the vortex stabilization is terminated near the trailing edge just upstream of the separation point, so that the vortices begin to wiggle around, inhibiting separation there like conventional streamwise vortices. The combination of reduced skin friction and reduced drag due to separation may be enough to pay for the vortex generator drag. Note that for a lifting airfoil, the goal is not minimum drag, but rather maximum L/D. Since both L and D are unfavorably affected by premature separation near the trailing edge, there may be a net benefit to L/D, especially for high lift airfoils.

Compared to other approaches to drag reduction, the proposed stationary vortices have several attractive features. The size of the vortex generators and the wavelength are comparable to or larger than the boundary layer thickness. Unlike conventional riblets, which operate at the Kolmogorov microscale, the present geometry would not be contaminated by small dirt particles. There are no moving parts. There is neither active feedback nor electric power consumption.

Riblets operate at the microscale. According to persistence theory, their potential to reduce the wall fluxes is modest (Cotel and Breidenthal 1998). From dimensional considerations, the wall flux should be proportional to the square root of the ratio of the relevant diffusivity to the vortex rotation period. Only by making the rotation period large can the flux be substantially reduced. Experiments confirm that microscale riblets with small rotation periods only offer modest drag reductions, of order 10% (Bushnell and Hefner 1990, Bechert et al. 1997). In contrast, the persistent vortices in this work are large, with relatively long rotation periods. Our preliminary experiments have already demonstrated a 50% reduction in local heat flux at modest Reynolds number. At higher Reynolds number, the predicted effect is larger, going as $Re^{1/4}$.

4 Conclusions

A measure of stationarity, the intrinsic velocity ratio of a vortex near a surface is a fundamental parameter that controls the physics. Compared to the nonstationary limit, the physics is much different in the stationary limit. The addition of stationary vortices to a turbulent boundary layer yields laminar flow over a significant fraction of the wall.

Acknowledgements

This research was partially supported by the Office of Naval Research.

References

Balle GJ, Breidenthal RE (2002) Stationary vortices and persistent turbulence in Karman grooves. J. Turbulence 3:33-51

Bauer M (2006) Boundary layer turbulence measurements near a persistent streamwise vortex. Project Report, Department of Aeronautics and Astronautics, University of Washington

Bechert DW, Bruse M, Hage W, VanderHoeven, JGT, Hoppe G (1997) Experiments on drag-reducing surfaces and their optimization with an adjustable geometry. J Fluid Mech 338:59-87

Bushnell DM, Hefner JN (Eds.) (1990) Viscous Drag Reduction in Boundary Layers. Progress in Astronautics and Aeronautics 123

Cotel AJ, Breidenthal RE (1994) Persistence theory of stratified entrainment. Preprints of the Fourth International Symposium on Stratified Flows 4 Grenoble, France, June 29-July 2, 1994

Cotel AJ, Gjestvang JA, Ramkhelawan NN, Breidenthal RE (1997) Laboratory experiments of a jet impinging on a stratified interface. Exp Fluids 23:155-160

Cotel AJ, Breidenthal RE (1998) A new approach to drag reduction. Proc. Int. Sym. Seawater Drag Reduction, 22-23 July 1998, Newport, Rhode Island

Crow SC (1970) Stability theory of a pair of trailing vortices. AIAA J 8:2172-2179

Dawson OR (2005) The effect of persistent vortices on boundary layer behavior in flow along a wavy wall. M.S. thesis, University of Washington

Eibeck P, Eaton JK (1987) Heat transfer effects of a longitudinal vortex embedded in a turbulent boundary layer. ASME J Heat Transfer 109:16-24

Fransson JHM, Brandt L, Talamelli A, Cossu C (2005) Experimental study of the stabilisation of Tollmien-Schlichting waves by finite amplitude streaks. Phys Fluids 17 :054110

Gharib M, Rambod E, Shariff K (1998) A Universal Time Scale for Vortex Ring Formation. J Fluid Mech 360:121-140

Oster D, Wygnanski I (1982) The forced shear layer between parallel streams. J. Fluid Mech 123:91-130

Roberts FA, Roshko A (1985) Effects of periodic forcing on mixing in turbulent shear layers and wakes. AIAA Shear Flow Control Conference, Paper 85-0570

Schoppa W, Hussain F (1998) A large-scale control strategy for drag reduction in turbulent boundary layers. Phys Fluids 10(5):1049-1051

Widnall SE, Bliss DB, Tsai C-Y (1974) The instability of short waves on a vortex ring. J Fluid Mech 66:35-47.