Formation and propagation of shock-generated vortex rings

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Introduction

Explore compressible turbulence via the standpoint of compressible vorticity and its building blocks.

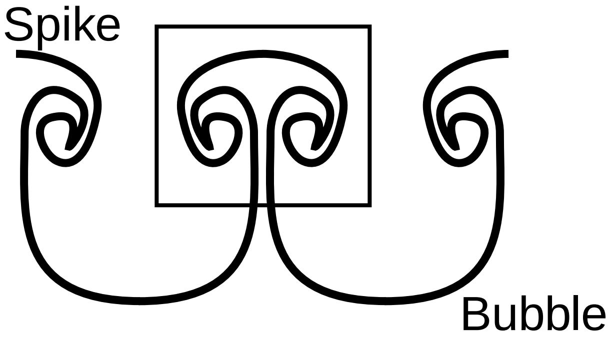
Compressible vorticity is also important from both fundamental and practical standpoints, in:

- Blade-vortex interaction, including sound generation, for rotary wing aircraft applications.
- Shock-vortex interaction, including sound generation, for jet noise applications.

Objectives

Experimental study of isolated vortices as building blocks of compressible turbulence.

For example, in the Richtmyer-Meshkov instability:



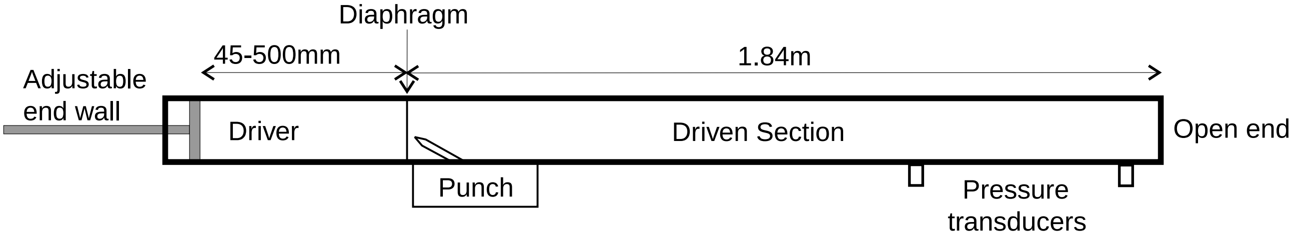
In particular,
— What exactly are compressible vortices?
— How are they different from incompressible vortical structures?

Specific experimental objectives

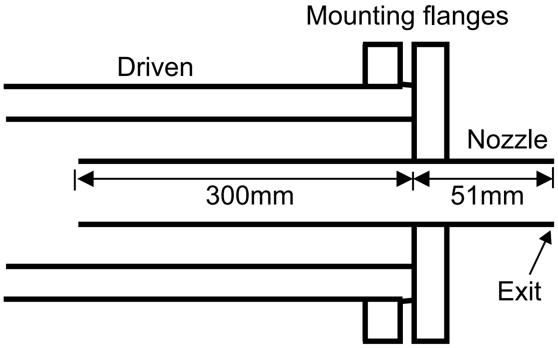
- Characterize the effects of the generator on the production and propagation of compressible vortices.
- Examine the effects of compressibility and scale on these properties.
- Compare with incompressible results.

Experimental considerations

Experiments are performed with a modified shock tube:



Open driven end, with 3 different exit nozzle diameters: 6.4, 12.7 and 25.4 mm

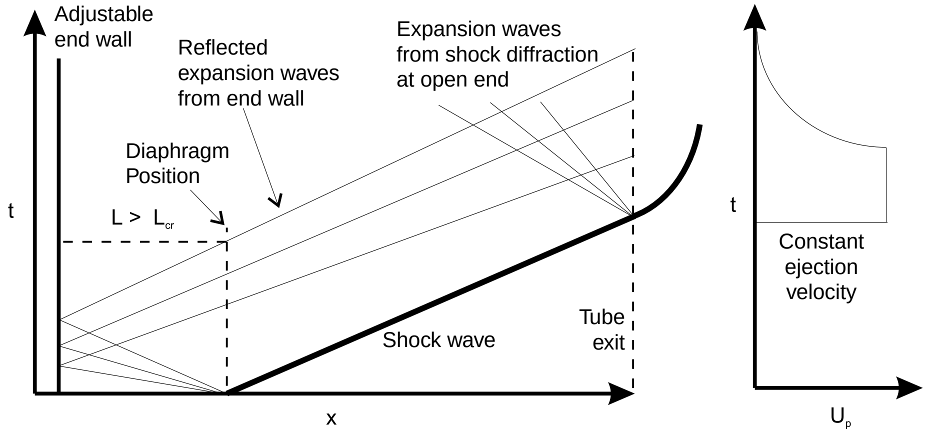


Features of this setup:

- Produce shear-driven vortices (Kelvin-Helmoltz instability) as opposed to baroclinically-driven vortices (Rayleigh-Taylor or Richtmyer-Meshkov instabilities)
- High vorticity production rates.
- Fluid piston analogous to high speed spike in RMI.

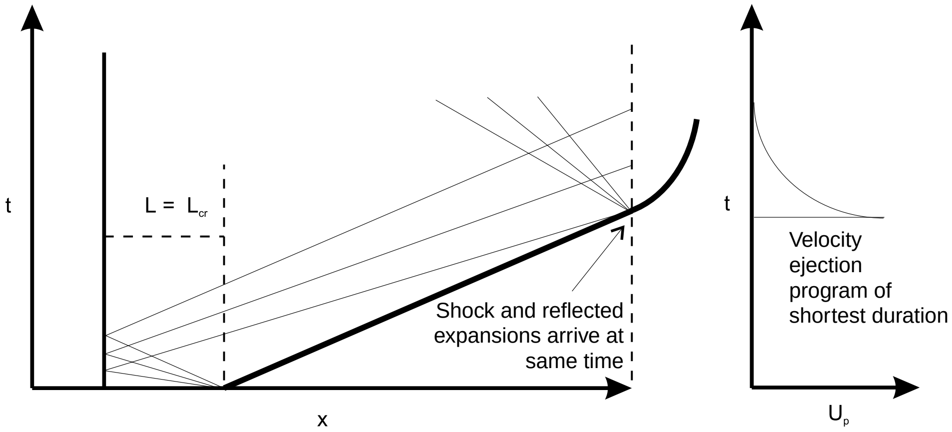
Effect of driver length on fluid ejection history

Standard (= long) driver



Analogous to RMI followed by RTI.

Tuned driver



Analogous to “almost only” RMI.

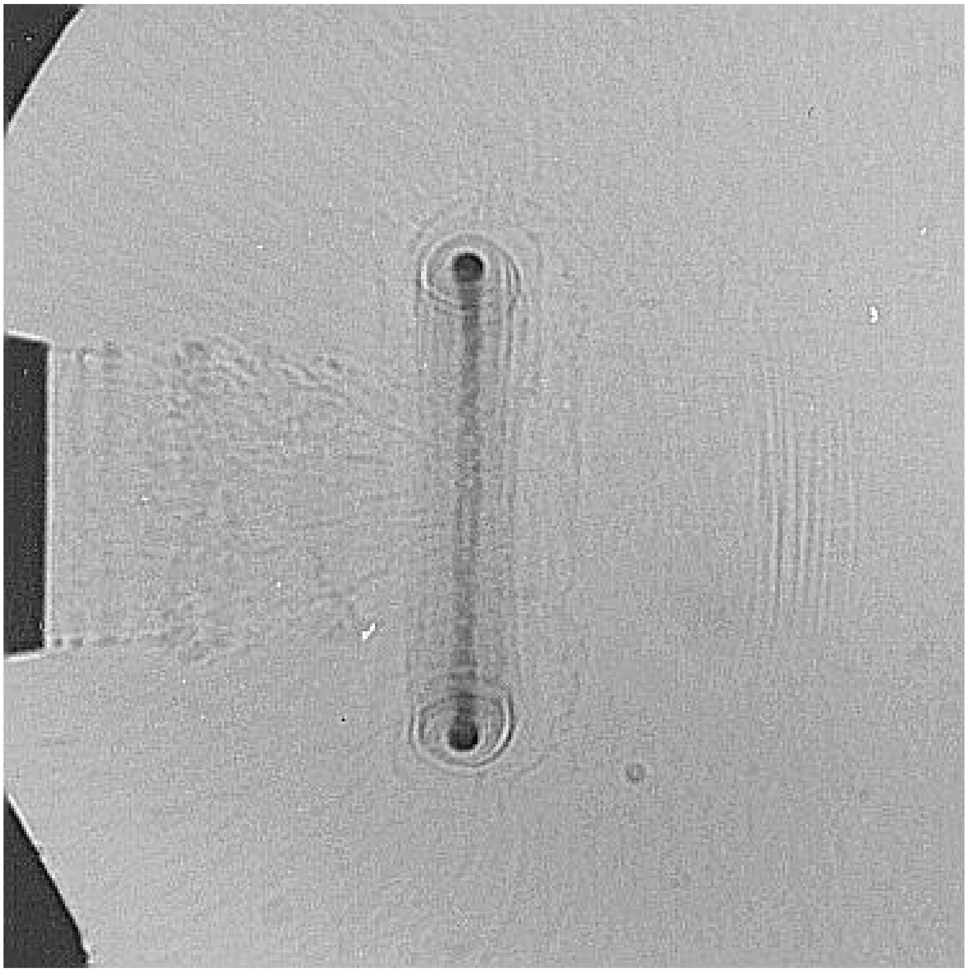
Flow diagnostics

- Piezoelectric pressure transducers.
- Flow visualization (shadowgraph, schlieren, holographic interferometry).

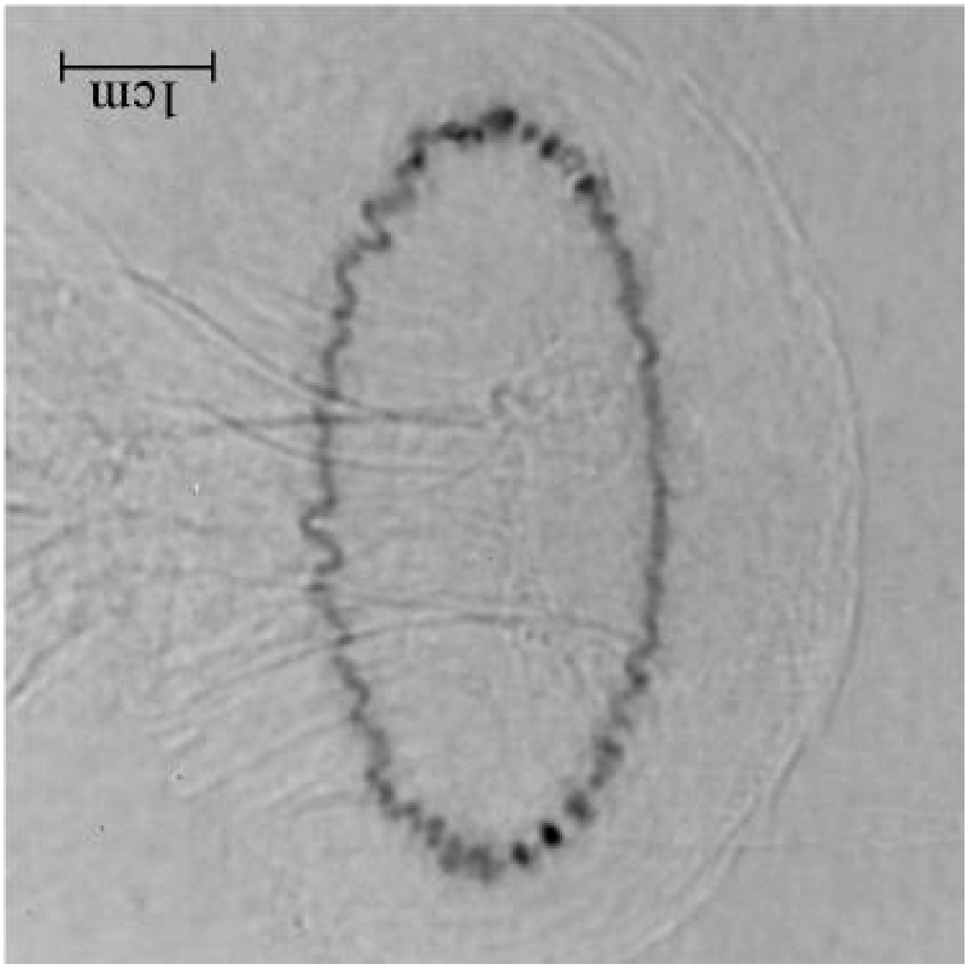
Vortex propagation

Three regimes of propagation

Low shock Mach number → regime 1



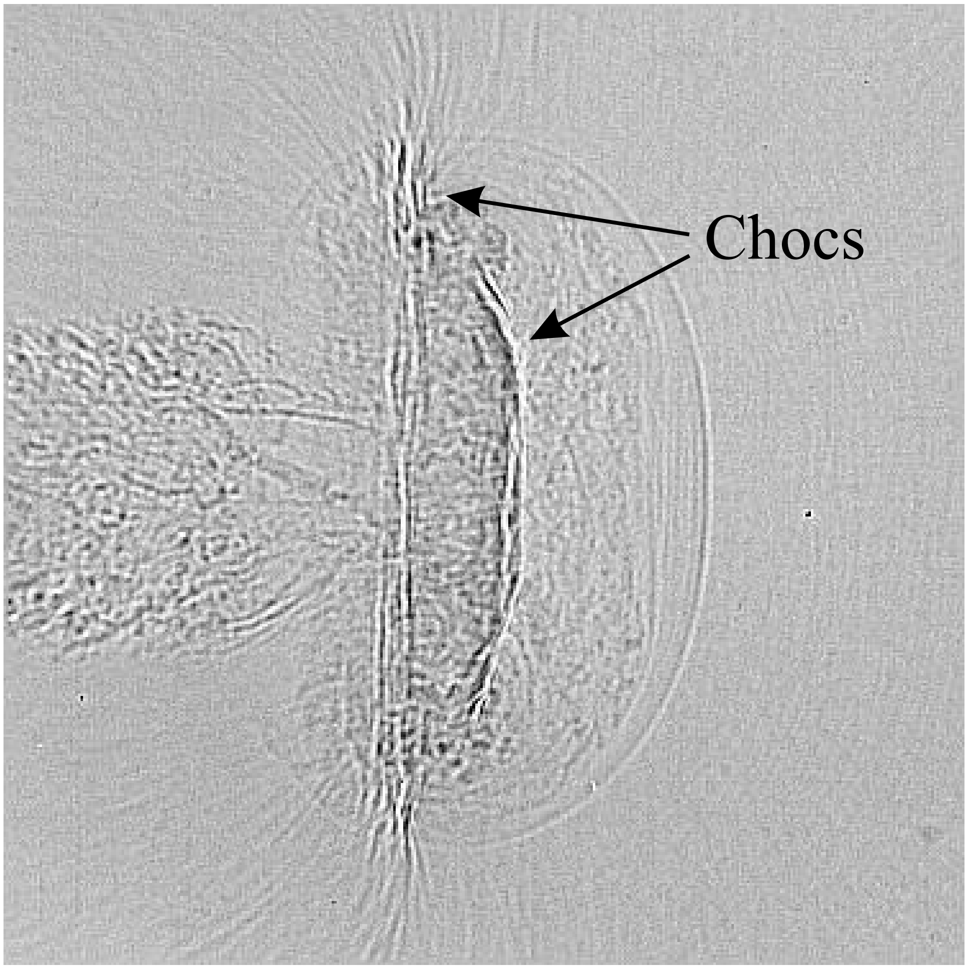
Regime 1 — Development of circonferential instabilities (oblique view)



Oblique spark shadowgraph, $M_s = 1.32$, $D_p = 38$ mm: $t = 1.42$ ms, $x/D_p = 3.30$

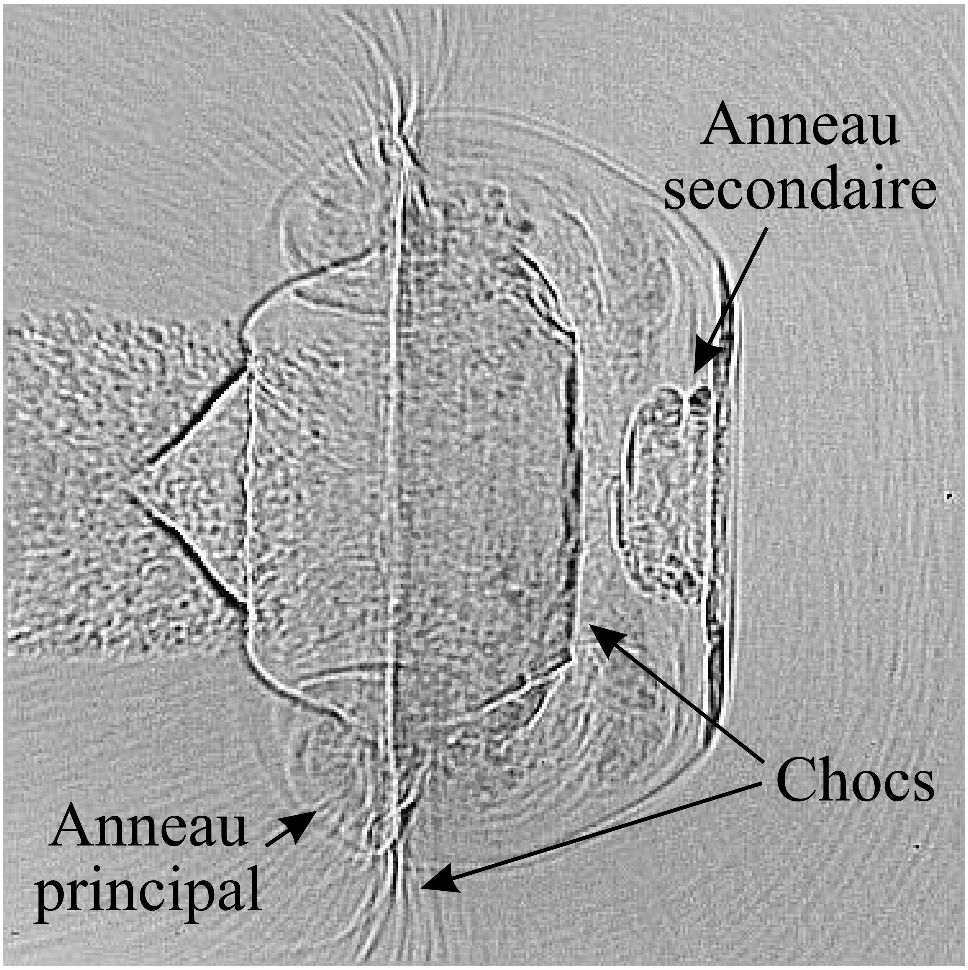
As M_s is increased:

Regime 2 — Appearance of shocks



As M_s is further increased:

Regime 3 — Secondary vorticity generation



Vortex propagation (37 mm orifice)

	Standard driver	Tuned driver
Regime 1	$1 < M_s < 1.34$	$1 < M_s < 1.44$
Regime 2	$1.34 < M_s < 1.45$	$1.44 < M_s < 1.60$
Regime 3	$M_s > 1.45$	$M_s > 1.60$

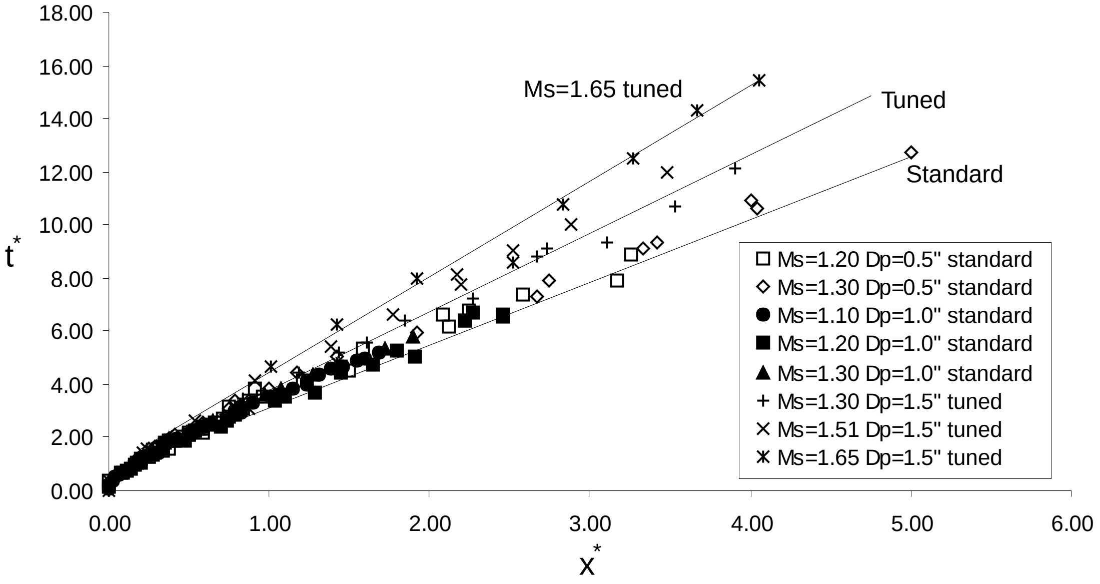
We know that for the same shock Mach number, impulse is larger for standard driver.

Regimes appear at lower Mach numbers for the standard case.

Vortex propagation — Position vs time

Results normalized with orifice diameter D_p and maximum fluid velocity U_p as:

$$x^* = \frac{x}{D_p} \qquad t^* = \frac{tU_p}{D_p}$$



Observations:

- Speed of vortex rings increases with shock strength.
- Rings produced with the tuned driver propagate slower $U^* \approx 0.34$ than with the standard driver $U^* \approx 0.42$.
- Within experimental error, not possible to detect compressibility effects.

Vortex formation

In incompressible experiments, typically use a piston to eject a slug of fluid (liquid).

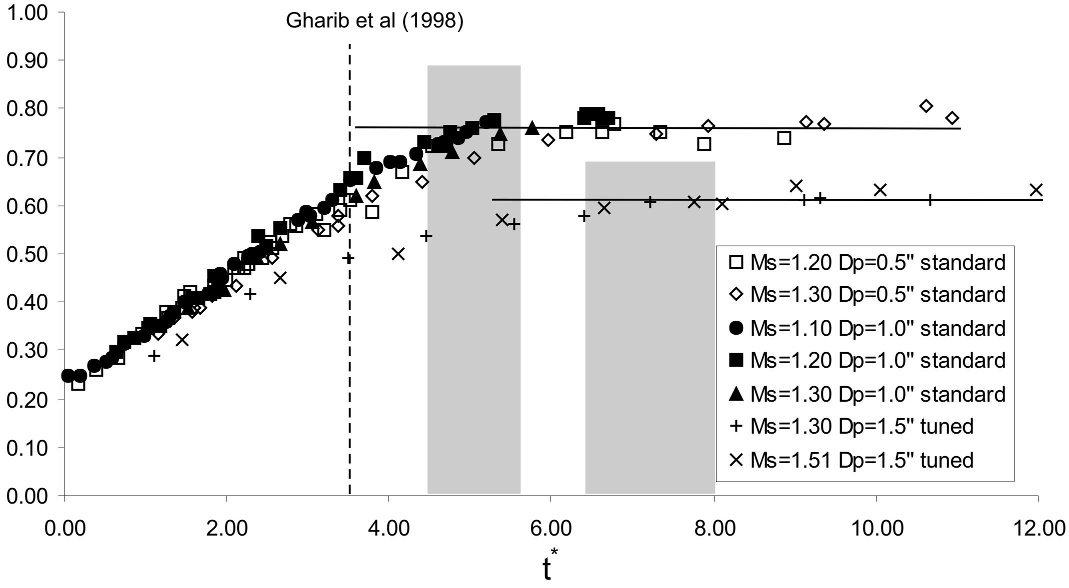
- Ejection Mach number near zero.
- Normalized ejected slug length relatively much smaller than in the present study.
- Vortex propagation mostly free from the effects of the generating jet.

Examine vortex formation in terms of circulation deposition history:

Use a normalized circulation

$$\Gamma^* = U^* d^*$$

Normalized circulation vs normalized time

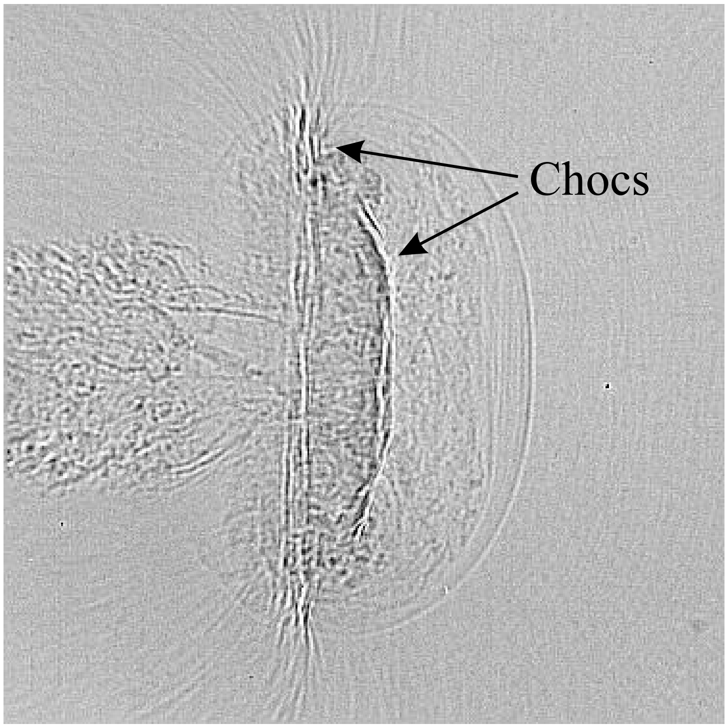


Observations:

- Vortex ring is formed when a vorticity saturation threshold is reached.
- Concept of vortex formation number (Gharib et al. 1998).
- Formation number higher for compressible rings.
- Maximum circulation similar between incompressible results and standard driver results.
- Lower circulation with tuned driver.
- Non-zero “initial” circulation (purely impulsive ejection history).

Other features — Shock formation by vortex

Onset of appearance of shock wave within recirculating region:



For the standard driver, this shock appears at $M_s = 1.34$ ($U_p = 339$ m/s).

For the tuned driver, this shock appears at $M_s = 1.44$ ($U_p = 425$ m/s).

This threshold is reached when flow velocities within ring recirculating region become sonic $u/c = 1$.

But since $u \sim \Gamma/d$ this threshold occurs when:

$$\frac{\Gamma}{d\ c} = 1$$

With $\Gamma \sim Ud$, then $\Gamma = \Gamma^*\ U_p\ D_p$. and this threshold can then be expressed as:

$$\frac{\Gamma^* U_p D_p}{d\ c} = 1$$

If this criterion is satisfied for both tuned and standard cases, then:

$$\frac{\Gamma^*_{tuned}\ U_{p_{tuned}}\ D_{p_{tuned}}}{d_{tuned}\ c_{tuned}} = \frac{\Gamma^*_{std}\ U_{p_{std}}\ D_{p_{std}}}{d_{std}\ c_{std}}$$

For identical test gases $c_{tuned} = c_{std}$, for identical orifices $D_{p_{tuned}} = D_{p_{std}}$ and we observe that $d_{tuned} = d_{std}$. Therefore

$$\frac{\Gamma^*_{tuned}}{\Gamma^*_{std}} = \frac{U_{p_{std}}}{U_{p_{tuned}}}$$

is satisfied if postulate is correct!

Experimental data:

Standard driver: $\Gamma^*_{std} = 0.76$

Tuned driver : $\Gamma^*_{tuned} = 0.61$

$$\frac{\Gamma^*_{tuned}}{\Gamma^*_{std}} = 0.80$$

Standard driver: transition at $M_s = 1.34$ $U_{p_{std}} = 339$ m/s

Tuned driver: transition at $M_s = 1.44$ $U_{p_{tuned}} = 425$ m/s.

$$\frac{U_{p_{std}}}{U_{p_{tuned}}} = 0.80$$

at the onset of appearance of the shock within the recirculating region.

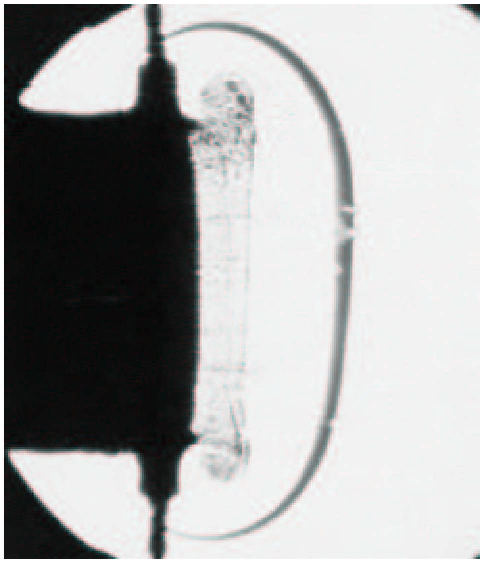
Postulate appears satisfied!

- For a given size, shock appears at a given ring circulation.
- The estimation of ring circulation rests on solid ground.

Consequences:

In a compressible turbulent flow, shocklets would appear if sufficient vorticity is locally present.

For a purely impulsive (delta function) fluid ejection history, since the maximum vorticity deposition Γ^* is small, a shock would appear at a very large ejection velocity. Our limited experiments at $M_s = 2$ support this.



Conclusions

- The behavior of compressible vortices is somewhat similar to that of incompressible vortices, but they attain circulation saturation slower.
- Vortex rings can only absorb a maximum amount of circulation.
- The most sustained and higher vorticity production rate lead to faster normalized formation and higher circulation.
- Can use this point of view to explain he appearance of shocks within vortical structures.