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Bluff-Body Wakes, Dynamics and Instabilities

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Wake Patterns of a Piston Gliding in a Rotating Circular Duct

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Summary

The flow around a piston gliding in a rotating circular duct filled with a liquid is observed experimentally. For Re-numbers up to ≈ 1150 the flow is laminar and stationary. The streamline patterns in front and behind the body are 3-dimensional and of different structure. At increasing Re-numbers an oscillatory mode appears. It originates from the back wake of the body and is accompanied by a train of separated flow regions propagating slowly along the channel to the front wake where they disappear.

Introductory Remarks

If a body moves in a narrow duct an additional wake that propagates upstream is generated at its front face. It is a consequence that most of the oncoming fluid cannot pass through the gap formed by the surrounding channel but is reversed into upstream direction. In a corresponding way the downstream wake is generated. Flows of this type are encountered in many technical applications like compressors or combustion engines but also a liquid flow in a tube interrupted by gas bubbles or a train running in a tight tunnel are good examples.

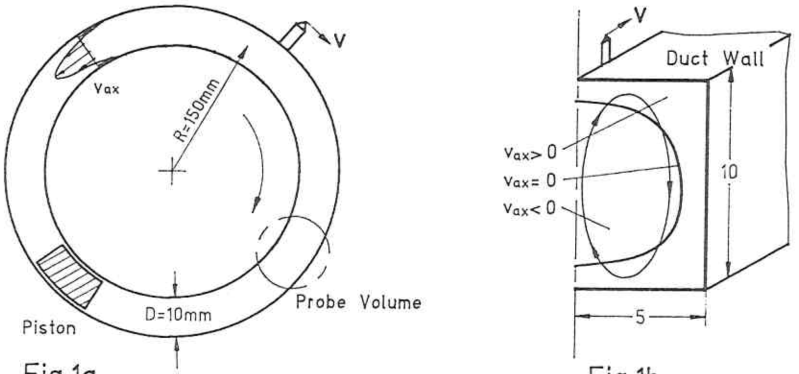

Fig.1a

Fig.1b

Fig. 1: *Scheme of the ring-shaped duct.*
1a: *Profile of the axial velocity* v_{ax} *and contour of the piston in the centre symmetry plane. If the duct is rotated at moderate velocities the piston is lifted to a stable equilibrium position.* v *is the velocity of the duct at its mean radius R=15cm. The direction of* v *is marked in all figures by an arrow fixed to a pointer outside the duct. All velocities are observed from the lab system.*
1b: *Regions of different axial velocity directions and principal shape of a streamline due to secondary motion in an azimuthal cross section of the duct. Only half of section up to the centre symmetry plane is displayed.*

Experimental

The experiments to be presented here are performed in a closed transparent circular duct of a mean radius of curvature of R=15cm and a square cross section of D=1cm side length. The cross section of the piston is also of square shape and fills 80% of that one of the duct. To reduce the friction between the duct walls and the piston and to guide the latter one symmetrically inside the duct, teflon spacers are mounted on the piston. As a flow medium glycerol-water mixtures are used in which small tracer particles of about 150µm are suspended. By rotating the duct slowly (≈1 rps) in a vertical plane around its axis of symmetry the fluid is convected by viscous forces and the metal piston is lifted till it reaches a stable equilibrium position. There, the piston is at rest and one has -at least for low Re-numbers- a stationary flow that can be easily observed. Conventional optical methods like PIV and a special visualization technique developed by Bartels et al. [1] that allows for on-line discrimination between "slow" and "fast" traces are applied. Also of importance for the investigation of the topological structure of the flow is the visual inspection of the tracer paths for which a stereo-microscope is used. Since the flow system is closed the wake generated at the front of the body is directly connected with that one emerging at its rear side. In rough approximation the flow structure can be described by an outer zone that is convected with the moving walls and a core region that moves into opposite direction. At the end faces of the piston these two regions are reconnected in a complex way. A schematic view of the duct and a typical velocity profile at some distance of the piston are displayed in Fig. 1.

Results

For low Re-numbers (Re= V·D/ν, with V mean velocity of the duct relative to the piston, ν kinematic viscosity of the liquid) the flow is laminar and stationary. At the back side of the piston where the streamlines change from the core to the wall region a torus shaped separated flow regime appears. As the flow is 3-D due to the curvature of the duct the dead-water is not completely closed. Some of the more outer core streamlines enter it at the inner perimeter of

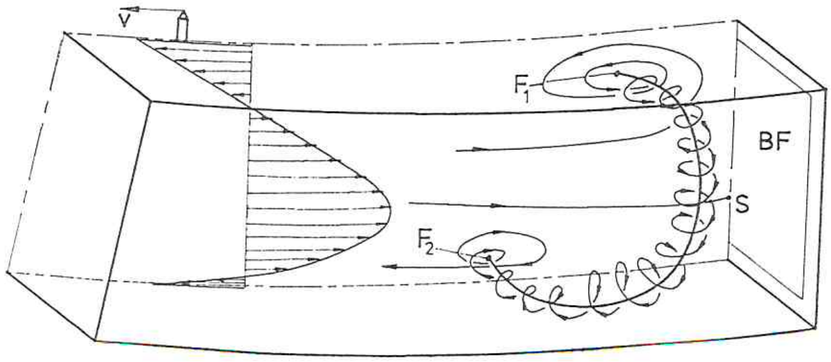

Fig. 2: *Flow structures behind the back face* BF *of the piston. For low velocities streamlines spiral around the torus shaped vortex core from focus* F_1 *to focus* F_2. *Foci and stagnation point* S *lie on the centre symmetry plane marked by a dashed line. Centre downstream axial velocity profile is not to scale. Only one half of the duct section is displayed.*

Fig. 3: *Flo*
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Fig. 4: *Flow*
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Fig. 5: *Flow*
focus F_2 *to f*

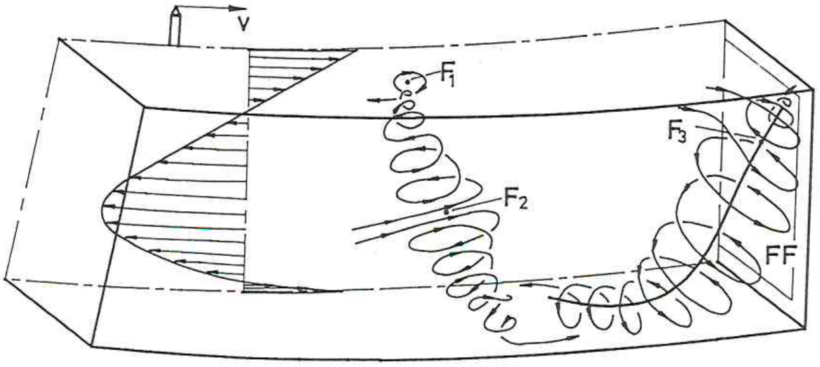

Fig. 3: *Flow structures ahead of the front face* **FF**. *Focal point* $\mathbf{F_1}$ *lies on the center symmetry plane,* $\mathbf{F_2}$ *and* $\mathbf{F_3}$ *are shifted towards the side wall of the duct. Upstream centre axial velocity profile not to scale.*

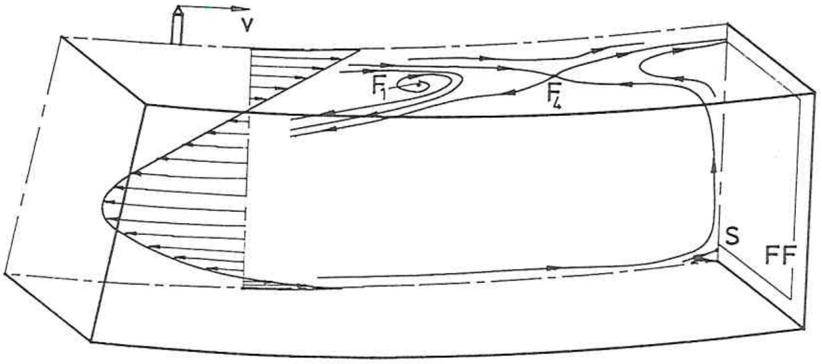

Fig. 4: *Flow structures on the centre symmetry plane ahead of the front face.* $\mathbf{F_4}$ *is a saddle point*

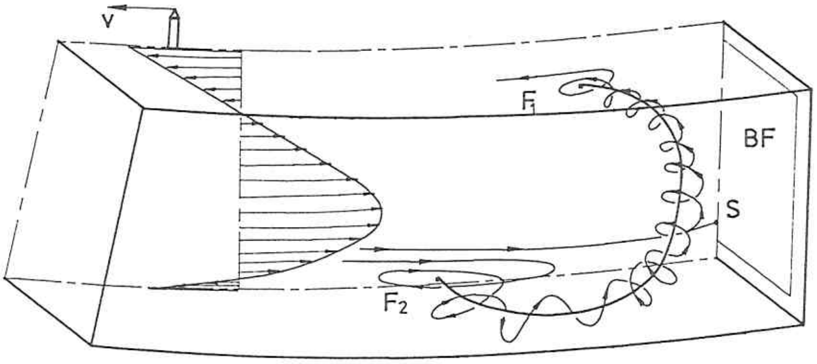

Fig. 5: *Flow structures behind the back face for Re > 340. Streamlines spiral around from focus* $\mathbf{F_2}$ *to focus* $\mathbf{F_1}$ *. The stagnation point* **S** *is shifted closer to the outer wall of the duct.*

the duct and spiral around the axis of the torus into the direction of the outer duct wall where they leave (Fig. 2). The streamlines of the central core impinge directly on the rear face where they are deflected by 180° in one turn into the opposite direction. On the front side of the piston the flow approaches from the wall region. Its main portion is reversed into the centre of the duct and forms the core region. Only a small fraction passes through the gap. In front of the body a complex system of vortices (Figs. 3,4) appears that up to now is not fully analysed. Some channel depths D upstream and downstream of the piston the flow looks quite similar to that one expected for a curved channel and also the two counterrotating cells are visible (Fig.1b). The position of maximum axial velocity is shifted to the outer duct wall.

If the Re-number is raised up to appr. 340 the flow direction along the axis of the torus shaped dead-water bubble is reversed (Fig. 5). For this Re-number the location of the maximum of axial velocity and consequently also the position of the stagnation point are now so close to the outer wall of the duct, that the direction of the radial velocity components changes. The structures in front of the piston seem to remain unaffected. The transition between these two states shows hysteresis.
At Re ≈ 1140 (Dean-number ≈ 208) the flow becomes oscillatory. Some channel depths downstream the back face of the piston the radial flow component on the centre symmetry plane, that up to this value of Re has been positive, reverses suddenly its direction in the neighbourhood of the outer perimeter. This reversal becomes visible by the appearance of a saddle point (Fig. 6). This flow configuration is conveyed at a very low speed along the duct to the front face of the piston where it disappears in the wake. Shortly after this cycle has been started the flow reattaches again and after some moments a new saddle point is established.

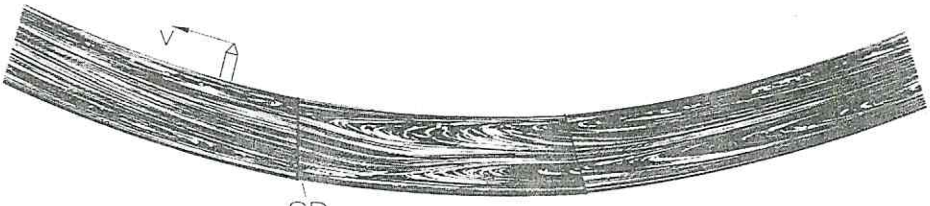

Fig. 6: *Particle traces in the centre symmetry plane for oscillatory flow conditions. The image is composed of three individual photos taken at different times at the same location. Mean velocity of duct wall 75.3cm/s, of saddle point* SP *7.2 cm/s. Re=1350, De=247.*

In the duct considered here a series of about seven saddle points may be observed at a time moving along the duct. Each of the saddle points is accompanied by the appearance of a second pair of cells located between the outer wall and the original cells. Their sense of rotation is opposite to that one of the first pair displayed in Fig. 1b. On the inner wall the velocity direction remains unchanged.

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For the laminar flow through a curved duct at rest the stationary and unstationary four cell mode is well known and has been investigated experimentally by e.g. Hille et al. [2] and Ravi Sankar et al. [3] and theoretically e.g. by Winters [4]. In a rotating duct only the unsteady case relative to the piston has been observed. A further increase of Re results into a more and more stochastic generation of saddle points and finally ends up in disordered motion. Whether there are additional periodic or even stationary states is not known at the moment. At present, we are planning a more detailed investigation of the 3-D structure of the oscillatory mode and a survey of the higher Re-number regime.

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