Engineering Notes

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Lift and Drag Measurements of Two Rotating Cylinders

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Introduction

LIFT and drag measurements with two rotating cylinders have been performed in order to test the balance described in Ref. 1 under difficult conditions where relatively small forces had to be measured and mechanical vibrations occurred. Rotating cylinders at an angle of attack create high lift and show a new behavior of the rear stagnation point which is different from the Kutta-Joukowski condition. At the zero lift condition $\alpha = 90$ deg the complete elimination of the pressure drag is realized.

Potential Flow Analysis

The potential flowfield around two cylinders (Fig. 1) can be described by conformal mapping of the dipole row from the ξ- plane into the z-plane with the transformation $z = -(a/2\xi)$. The complex potential is

$$\chi(z) = -iw_\infty a\pi \operatorname{cotan}(\pi a/z)$$

If a lift force is generated, the magnitude Γ of the corresponding vortex depends only upon the angle α of the flow and the angular location φ_r of the rear stagnation point. The potential flow can easily be calculated by superimposing the complex potentials for the selected rear stagnation point location. If the stagnation point is assumed to be located in the slot between the two cylinders, the lift coefficient based on $b = 4 \cdot a$ in Fig. 1 is

$$c_\ell = \pi^2 \cos\alpha$$

The maximum theoretical lift coefficient $c_{\ell max} = 9.87$ occurs at $\alpha = 0$ deg and is also the maximum for all other conditions where both stagnation points fall together on one point anywhere on the cylinder surface. Figure 2 shows the lift coefficient as a function of the stagnation point location φ_r. The flowfield and corresponding pressure distribution for $\varphi_r = 180$ deg and $\alpha = 45$ deg are shown in Fig. 3.

Experimental Setup

The experiments were performed in the subsonic wind tunnel of the ETH which has a 3×2.1 m test section.[2] In order to minimize end effects due to separation of the wind tunnel wall boundary layer, a small diameter (0.105 m) had been selected giving a large span (2.1 m) to diameter ratio. The cylinders were made of light alloys with a wall thickness of 1.5 mm in order to avoid large rotating masses. They were driven by a speed-regulated dc motor mounted on the upper end of the vertically installed cylinders.

On the lower end, the cylinders were attached to the wind tunnel balance. Membrane supports on each end helped to separate the aerodynamic forces.[1]

The wind tunnel wall boundary layer tends to separate in the vicinity of the rotating cylinders, thereby creating additional drag. This can be eliminated by suction through

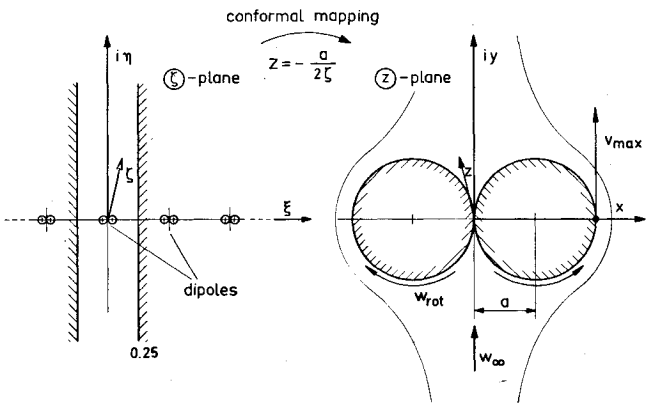

Fig. 1 Basic conformal mapping procedure to obtain a potential flowfield around two cylinders. Under real flow conditions, the flowfield can be achieved by rotating the cylinders.

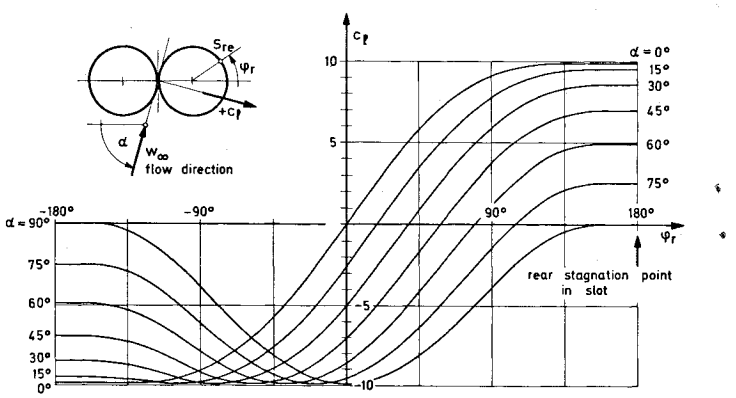

Fig. 2 Lift coefficient c_ℓ of two cylinders in function of α and the rear stagnation point location φ_r.

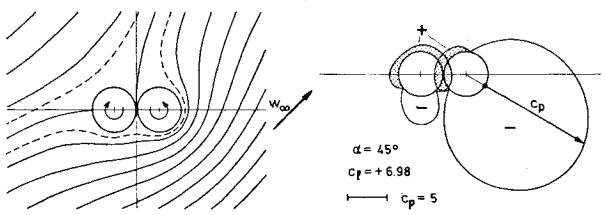

Fig. 3 Potential flowfield and pressure distribution around two cylinders, $\alpha = 45$ deg; $\varphi_r = 180$ deg.

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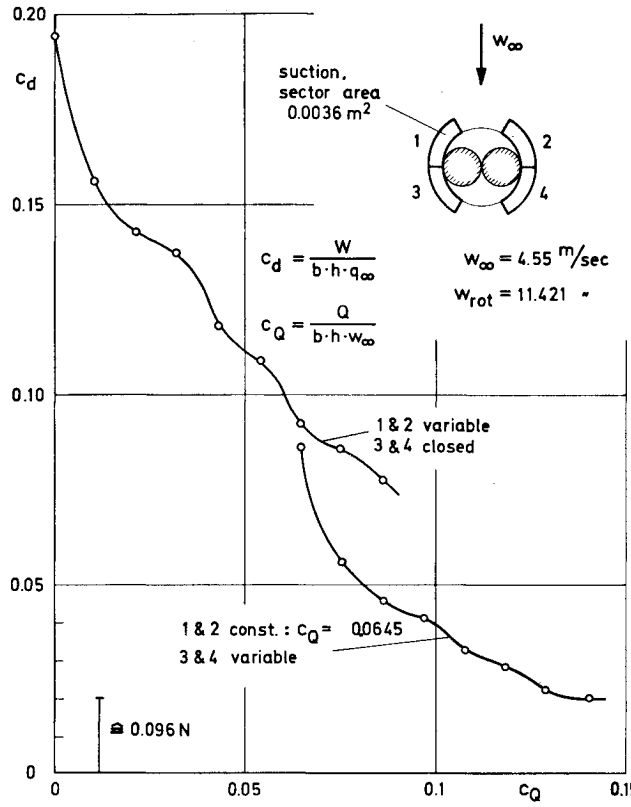

Fig. 4 The remaining drag due to end-wall separation can be eliminated with suction through the wind tunnel wall (c_Q is indicated for both walls).

perforated sheets attached to the wind tunnel wall. During the investigation it was found that it was most effective to apply the suction very close to the cylinders through relatively small sectors. The drag could in this way be reduced by 90% (Fig. 4).

Discussion of Results

The drag measurements were made at $\alpha = 90$ deg, where the flowfield takes the shape shown in Fig. 1. No flow separation should occur if the potential flow velocity $v_{max} = 2.472\ w_\infty$ is equal to the rotational speed w_{rot}. As the momentum in the

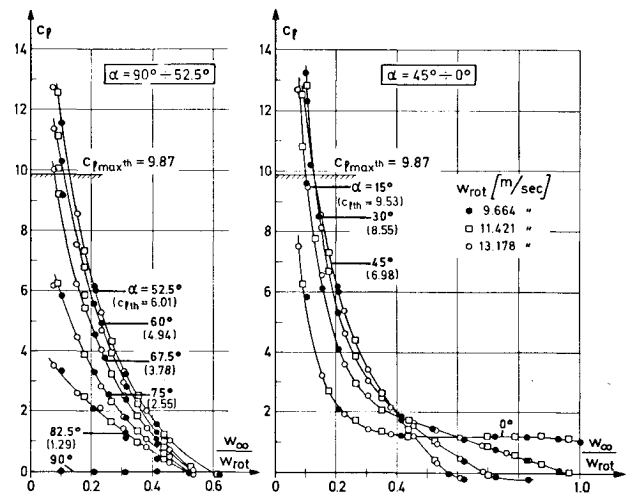

Fig. 6 Lift measurements of the rotating cylinders as a function of w_∞ / w_{rot}. Three different rotational speeds have been investigated. Theoretical values c_{fth} are indicated for $\varphi_r = 180$ deg.

boundary layer close to v_{max} is higher than in the adjacent free flow, a considerably lower value than $w_{rot}/v_{max} = 1$ would be expected before separation of the turbulent boundary layer occurs. However, Fig. 5 shows the drag-rise to start as soon as $w_{rot}/v_{max} < 1$. The suction arrangement corresponded to the optimum solution where suction is applied in thz sectors 1 to 4 (Fig. 4). The rate $c_Q = 0.14$ for $w_\infty = 11.421$ remained constant but was adapted for the other rotational speeds. The drag-plateau for $0.6 < w_{rot}/v_{max} < 0.9$ shown in Fig. 5 is not associated with the applied wall suction but is due to a weak vortex-street disappearing below $w_{rot}/v_{max} = 0.6$. Within the limits of the investigation, drag does not depend on Re but only on the ratio w_{rot}/v_{max} (Fig. 5). If the ratio is increased to values considerably above 1, the wake is replaced by a jet. The resulting thrust could not be clearly measured due to its small magnitude compared to the vibration forces of the rotating cylinders.

The lift measurements were carried out between 0 deg $\leq \alpha \leq 90$ deg with three different rotational speeds, $w_{rot} = 9.664$, 11.421 and 13.178 m/s. The forces and the flowfield depend only on the ratio w_∞ / w_{rot}. The point c_{fth} indicates the theoretical lift coefficient obtained with the rear

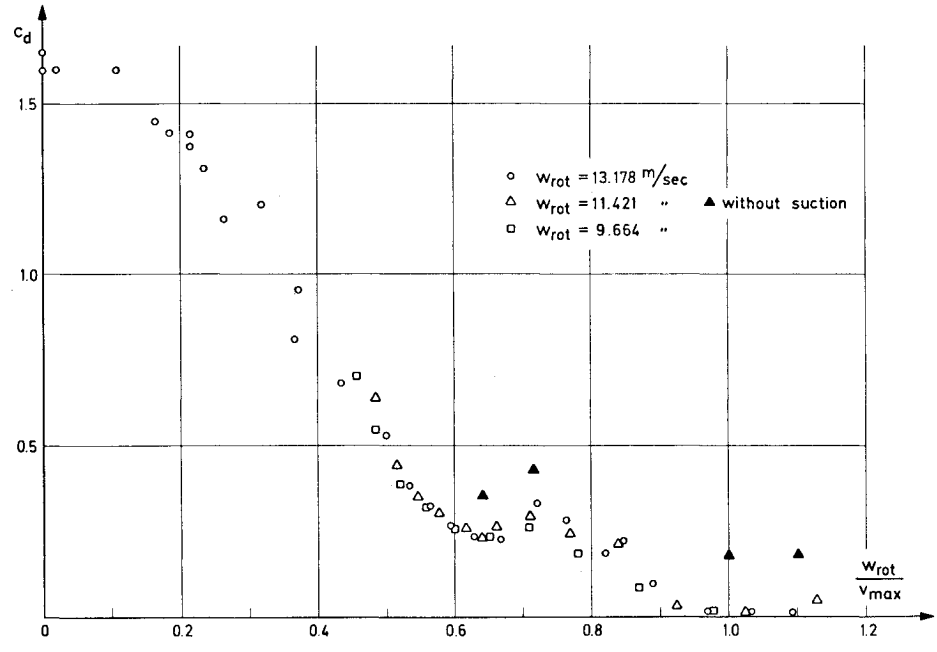

Fig. 5 Drag coefficient of two contrarotating cylinders as a function of the rotational speed to the maximum velocity w_{rot}/v_{max} where $v_{max} = 2.472\ w_\infty$.

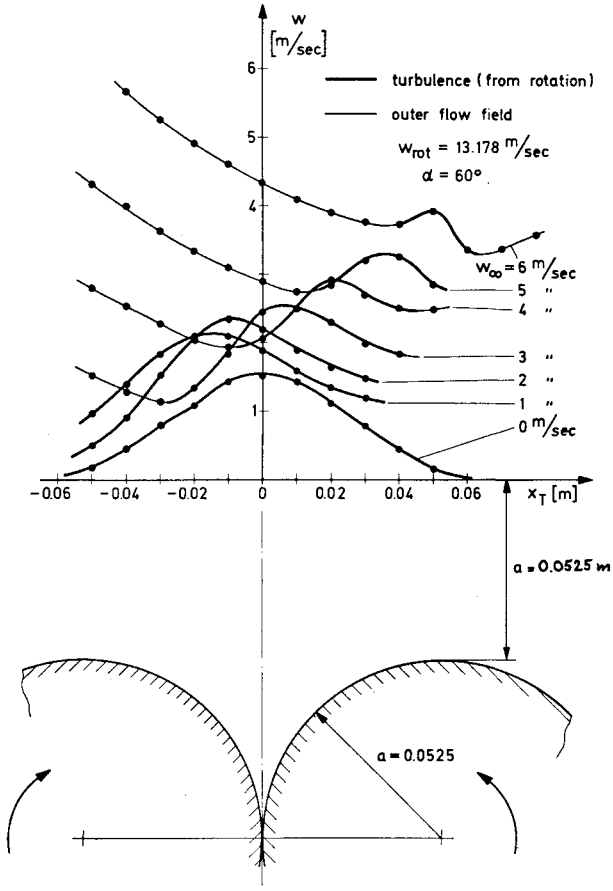

Fig. 7 Velocity distribution behind the rotating cylinders, measured with hot wire probes.

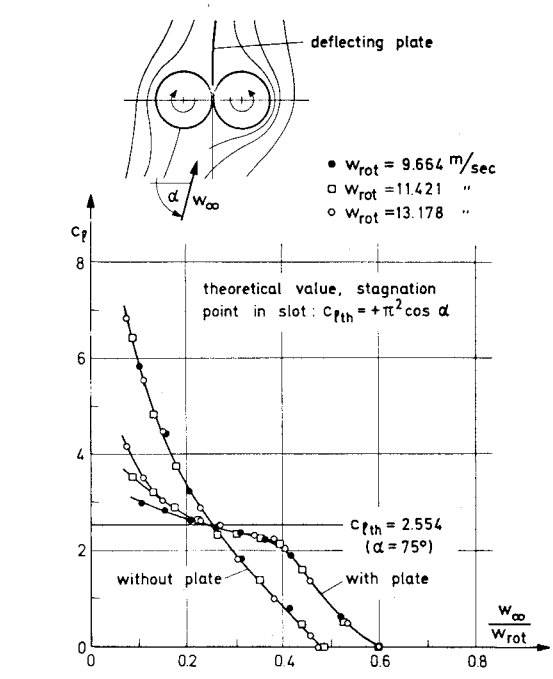

Fig. 8 Influence of a deflecting plate behind the cylinders. The theoretical values for φ_r = 180 deg can be achieved.

stagnation point located in the slot between the two cylinders as shown in Fig. 3. This condition is valid for one ratio w_∞ / w_{rot} only and is therefore not generally applicable. In the region of 52.5 deg $\leq \alpha \leq$ 90 deg (lefthand side of Fig. 6), no pressure drag was measured for $w_\infty / w_{rot} \leq 0.40$. In the case of $\alpha = 90$ deg where no lift force is generated, the optimum velocity ratio based on the drag measurements was $w_\infty / w_{rot} = 0.405$.

The lift coefficients c_ℓ in the region 0 deg $\leq \alpha \leq$ 45 deg (righthand side of Fig. 6) show a different behavior indicating that viscous forces degrade the lift-to-drag ratio of the cylinders. Large portions of the cylinder walls move against the general flow direction causing local flow separations to occur. At $\alpha < 75$ deg the measured lift exceeded the maximum theoretical value of $c_{\ell th} = 9.87$. However, the measurements at the corresponding very low ratios w_∞ / w_{rot} are not so accurate due to the low flow velocity (on the order of 1 m/s or less). Of course the jet formed by the cylinder boundary layer should cause some additional lift.

In order to understand the flow conditions at the rear stagnation point the velocity distribution behind the cylinders was measured with hot wire probes (Fig. 7). The profile of the jet for different flow velocities shows a distinct displacement to the right towards the freestream flow direction when w_∞ is increased. At low free stream velocities the jet determines the location of the outgoing streamline and thereby the whole flowfield. This is confirmed by tests with a deflecting plate attached to the wind tunnel wall and located just behind the cylinders (Fig. 8).

The curve is approaching the theoretical value $c_{\ell th} = 2.554$ for decreasing w_∞ / w_{rot} with the exception of very low ratios of w_∞ / w_{rot}, where again the jet produced by the rotating cylinders dominates the flow.

Concluding Remarks

The flow around two rotating cylinders inclined to the flow direction is governed by the jet formed by the boundary layers on the two cylinders and associated interaction with the external flowfield. For velocity ratios $w_\infty / w_{rot} \leq 0.4$ and for angles of attack 90 deg $< \alpha <$ 52.2 deg, the tests indicate a greatly reduced or eliminated pressure drag.

A new concept of stagnation point control is demonstrated that is not based upon avoiding flow separation (the Kutta-Joukowski condition) as on the single rotating cylinder, but rather depends on the effect of the momentum of the two boundary layers of the rotating cylinders forming a jet that defines the downstream flow conditions.

References

[1] Bridel, G., and Thomann, H.H., "Wind Tunnel Balance Based on Piezoelectric Quartz Force Transducers," *Journal of Aircraft*, Vol. 17, May 1980, pp.

[2] Bridel, G., "Strömungsuntersuchungen an 2 rotierenden Zylindern mit einer neuen Mehrkomponentenwaage," Thesis No. 6108, Swiss Federal Institute of Technology, Zurich, Switzerland.

Aircraft Configuration Optimization for Ground Attack Mission

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$\mathcal{R}$	= wing aspect ratio
C_{D_0}	= profile drag coefficient
C_{D_B}	= base drag coefficient
C_{D_F}	= skin friction drag coefficient
C_{D_W}	= wave drag coefficient
C_L	= lift coefficient

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