# Wake-Vortex Sound Attenuation using Attached hairy Flaps

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## Introduction

Vortex shedding from cylinders is well known to induce tonal sound since the pioneering work of Strouhal [1]. In the past, much attention has been devoted to manipulate vortex shedding [2] and tonal acoustics [3] with active and/or passive means. Among them, a splitter plate attached at the aft of the cylinder base has been known to be one of the most successful ways for suppressing of vortex shedding at all [2], [4],[5]. Recently, flexible flaps have been considered by Kunze and Brücker to control the wake generated behind a cylinder. In particular, their device with hairy flaps on it proved that these flaps are able to modify the shedding cycle [6]. The study showed a characteristic jump in the shedding frequency at a critical Reynolds number of $Re_{\mathrm{c}} \approx 14{,}000$ when comparing to the classical behaviour of a plain cylinder wake flow. The analysis of the motions of the hairy-flaps showed that for $Re = Re_{\mathrm{c}}$ the amplitude of the flap motion is considerably increased and a characteristic travelling wave-like motion pattern could be observed along the row of flaps. As a consequence the presence of the hairy flaps alter the phase within the vortex shedding cycle such that the transversal dislocation (transversal distance from the centerline) of the shed vortices is reduced [6]. Accordingly, the vortices are not arranged in a classical zig-zag pattern of the Kármán vortex-street, rather they are shed in a row along the centerline.

In the present work the acoustic signature of this transition of the wake shedding cycle is studied. At first, we describe the geometry of the hairy-flaps and the experimental set-up. Then, experimental results in a water tunnel are shown to identify the influence of the hairy-flaps on the wake flow. Finally acoustic spectra are shown. A resonator model is proposed which describes the vortex shedding based on the characteristic length scale of the separation bubble.

## Experimental setup

The self-adaptive movable hairy flaps consist of a two component silicon rubber (Wacker Elastosil RT 601 with a Young Modulus of 1.2 MPa). The two components of the silicon rubber were well mixed, vacuumized and filled into a casting form. After the rubber was cured one single element of a hollow cylinder with hairy flaps was extracted from the casting form, see figure 1. The height of each element was H = 12mm and the outer diameter D = 30mm. Small rings with a thickness of 1mm were alternately placed in order to ensure a 1 mm gap between two consecutive flap rings. Finally 23 single elements were staggered on a cylindrically rod, resulting in a total height of 300mm. The length of one single hairy flap is l = 0.3D and its width w = 0.05D. The cylinders with hairy flaps were compared with a reference cylinder without hairy flaps (configuration left in figure 1) and a reference cylinder with an attached bluff body (configuration second left in figure 1). The shape and size of the bluff body is identical to the hull of the whole bundle of moveable hairy flaps.

The velocity field around similar test cylinders was measured in a preceding study by single plane 2D PIV in a water tunnel at Freiberg University. Therefore a laser light sheet (Continuum Minilight II – Nd:YAG Laser, 532nm) was spanned in the mid-plane of the model and one camera (PCO.1600 with a resolution of 1600x1200px at a recording frequency of 14Hz) was used to record the particle image displacements.

**Abbildung 1:** Models of the cylindrical test objects investigated within the anechoic wind-tunnel

In order to analyze the sound generation by the flow acoustic measurements were conducted in the small aeroacoustic wind tunnel at BTU Cottbus - Senftenberg. The setup is basically identical to that used in the study by Geyer et al. [7] on the noise generated by porous covered cylinders. It consists of an aerodynamically closed test section of approximately 1.5 m length that is mounted to the rectangular nozzle of the open jet wind tunnel, which has an exit area of 0.23 × 0.28 m. The two lateral sides of the test section are covered by tensioned Kevlar that allows sound waves to propagate from the flow region inside the test section to the outside. The upper and lower walls of the test section are made from thick acrylic glass. Figure 2 shows a photograph of this test section.

The wind tunnel allows for a maximum flow speed of about 60 m/s. The flow inside the test section can be described as virtually laminar, with turbulence intensities in the order of 0.2 %. For the measurements, the cylinders were positioned approximately 0.2 m downstream from the nozzle and centered between the two kevlar windows. The models were fixed to the acrylic glass walls on both

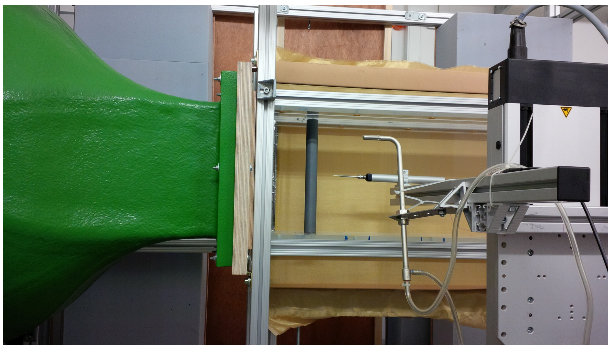

**Abbildung 2:** Photograph of the anechoic wind-tunnel with open side-wall

ends and hence, a generation of tip noise did not occur.

## Flow details

As documented in [6] the flow measurements show a transformation of the wake structure induced by the lock-in effect of the flap motion with the vortex shedding. All flow measurements were carried out in a range of Reynolds number $5000 \leq \mathrm{Re} \leq 31000$ defined with the main flow velocity and the diameter of the cylindrical front-part of the bluff body. Figure displays the time averaged flow field around two of the test cylinders at Re = 27750. The configurations with hairy flaps is compared with the reference cylinder without hairy flaps. The positions and silhouettes of the test cylinders are indicated in black and all velocity in the shadow region beneath the cylinders are blanked. The size of the recirculation area behind the cylinder with hairy flaps is notably smaller than the behind the reference cylinder. Therefore, the length of the separation bubble is reduced, too.

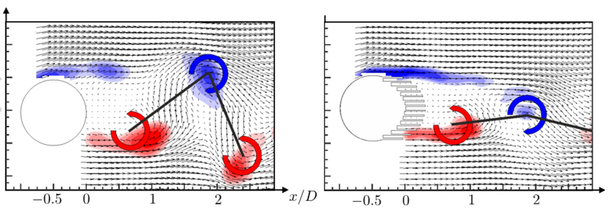


**Abbildung 3:** Comparison of wake flow pattern for reference cylinder (left) and hair flaps (right)

A further POD analysis of the vorticity field provides the distribution of the energy fraction of vorticity, see figure 4. The size and location of the vorticity modes are important for the comparison of the two cases. As seen, there is a significant influence of the motion of the hairy flaps on the flow. The transversal distance between the two symmetric vortices for the case with hairy flap is largely reduced. For the 2nd mode this distance is reduced to such a degree, that only one single vortex can be identified immediately downstream of the cylinder with hairy flaps. Considering the results of the POD-analysis and the velocity field it is concluded that the deflection of vortices in transveral y-direction is reduced due to the lock-in. Therefore, the vortices are not arranged in a classical zig-zag von Kàrmàn street pattern, but are alligned along a row wjhich is the symmetry-axis (y=0).

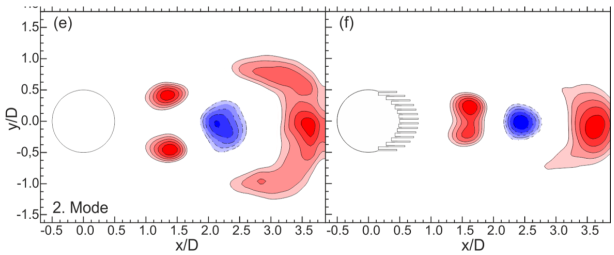


**Abbildung 4:** Comparison of 2nd POD mode of spanwise vorticity for reference cylinder (left) and hair flaps (right)

The transition is also seen in the Strouhal-Reynolds plot as given in the next figure 5. There is a clear jump in the non-dimensional shedding frequency at about a Reynolds-number of 20.000. The measurements of the flap kinematics show that this jump appears if the shedding frequency matches the first harmonic of the eigenfrequency of the flap bending mode. This clearly hints on a lock-in mechanism.

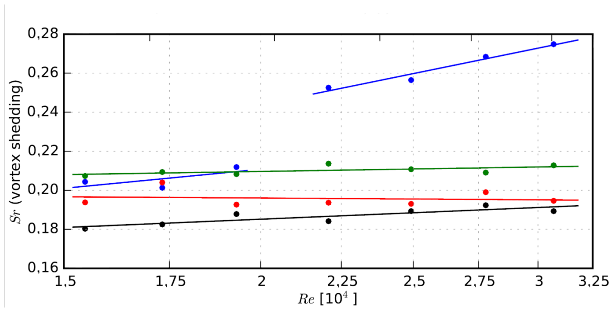


**Abbildung 5:** Plot of Strouhal over Reynolds-number for the reference cylinder (black line) and the hairy flaps (blue line)

## Acoustics

The results from the acoustic measurements show that the jump in the Strouhal-Reynolds relation is also found in the acoustic spectrum in case of the hairy flaps while neither of the other modifications replicates this behavior. Therefore the hairs affect the flow in air similar as observed in water in form of mode-locking. From the analysis of both the acoustic spectra as well as the flap motion, the following conclusion can be drawn: With increasing flow velocity oscillation amplitudes increase and finally around Re=Rec, the peak in the tonal sound spectrum jumps to a higher Strouhal frequency. This indicates that the shedding cycle has changed at the moment when the shedding frequency matches harmonics of the bending mode.

Our experiments show a correlation between the kinematics of the vortices and the length of the separation bubble. In detail, it is shown that the vortex-shedding frequency normalised with the length of the separation bubble and the incoming flow velocity is nearly constant. We therefore suggest that the classical formulation of the Strouhal number with the diameter of the cylinder as characteristic length scale is not suitable for the cases with hairy flaps, since the resonator model. Therefore,

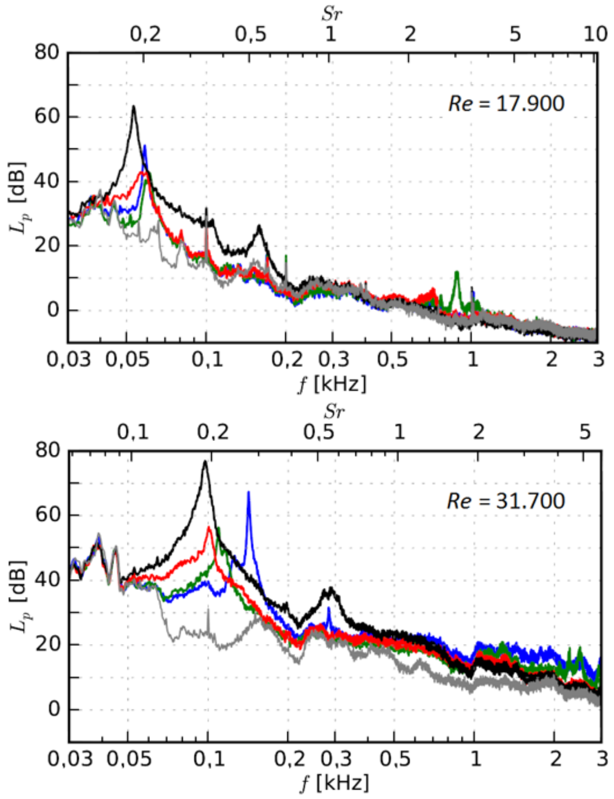


**Abbildung 6:** Sound spectrum for different Reynolds-numbers (black line: reference cylinder; blue line: hairy flaps)

an adapted Str number is calculated with the characteristic length scale x0 taken as the length of the separation bubble. Figure 7 shows the dependency of the adapted Str number from the Re number for the reference cylinder and hairy flaps. Only small variations along Re and between the cases can be found and no jump is seen at all.

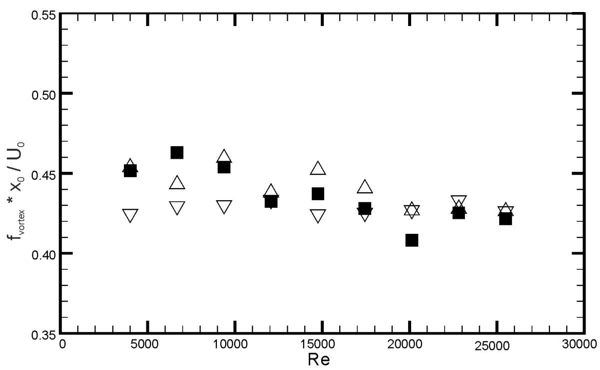


**Abbildung 7:** Adapted Strouhal-number over Reynolds-number for all cylinders.

## Summary

This study describes the modification of acoustic noise emitted from aerodynamic bodies (cylinders or foils) if equipped with flexible hairy flaps at the aft part as a passive way to manipulate the flow and acoustics. The study demonstrated that hairy flaps can modify the shedding cycle behind the cylinder and noticeably change the acoustic spectrum. The hairy flaps cause a sudden jump of the vortex sound frequency from Sr=0.2 towards higher Strouhal-numbers = 0.28 when resonant excitation of the flaps is present. That means the criterion for the jump is a critical amplitude of flap oscillations and occurance of lock-in of vortex shedding with the flap bending eigen-frequency. Besides the characteristic jump the hairy flaps enable a noticeable reduction of both vortex shedding noise as well as broadband noise compared to the reference cylinder. A similar trend is observed for other modifications. Therefore, these wake-manipulators could be applied in aerodynamic systems for noise reduction. Due to the practical importance of cylinder wakes in many engineering problems, it may have a valuable impact.

An additional outcome of the study is the proposed scaling of the shedding frequency (the Strouhal number) with the characteristic length-scale of the separation bubble instead of the traditional diameter of the cylinder. This scaling addresses the physical aspects of the coupled resonator which is modified by the presence of the flexible elements attached to the aft part of the cylinder. Therefore it takes into account all aspects of wake modification and allows comparison of the different configurations.

## Literatur

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