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On the optimisation of a cylinder/plate configuration with the aim to improve the energy harvesting of vortex induced vibrations

用以提高涡激振动能量收集之气缸/板结构优化

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Abstract - **With the objective of energy harvesting by use of vortex induced vibrations on a cylinder/plate configuration different approaches for maximising the amplitude of oscillation modes were pursued. By investigating the sound emissions of a small-scale cylinder/plate setup, a maximisation of the vortex-induced wall-forces on a rigidly mounted cylinder can be described. The surface-forces induce pressure fluctuations that propagate with the speed of sound and cause dipole shaped Aeolian tones. Thus, the present wall-forces of the cylinder directly correlate with the acoustic phenomena. Regression functions were formulated to describe the effect of the investigated parameters Reynolds number, turbulence intensity, plate length, plate thickness and vertical displacement between plate and cylinder, quantitatively for each analysed response variable. An optimal set of parameters can be defined with respect to the given boundary conditions that guarantees high surface-forces on the cylinder and consequently leads to an improved system.**

Keywords - **energy harvesting, vortex induced vibrations, aeroacoustics, cylinder/plate configuration**

I. INTRODUCTION

Given an elastically mounted cylinder in a steady flow, when exceeding a critical Reynolds number, vortices start to separate from the cylindrical surface. If the vortex shedding frequency (f_{VSF}), described by the Strouhal law in Eq. (1), equals the eigenfrequency (f_{Eigen}) of the cylinder-spring-system, a transition to an excited mode takes place and the cylinder starts oscillating.

$$f_{Eigen}\,[Hz] = f_{VSF} = {}^{Sr}/_{d_{Cyl.}} \cdot U_0 \tag{1}$$

Where Sr is the Strouhal number, $d_{Cyl.}$ the cylinder diameter and U_0 the incoming flow velocity. Use of the idle strokes of the cylinder, caused by vortex-induced vibrations (VIV), enables the harvesting of energy, Fig. 1. Especially energy-rich water flows offer great possibilities and good efficiencies for this new technological approach, even at low-speed conditions ($U_0 \leq 3$ m/s). Studies during the last decade promise good results and a huge range of applications such as wastewater flows or applications at riverbeds and beneath the floating platforms of offshore wind energy parks. One key issue of this system, when implementing in environmental applications, is the dependency of the system efficiency on a constant flow at a certain velocity, able to provide the matching vortex shedding frequency to the eigenfrequency of the system in order to guarantee the excitement.

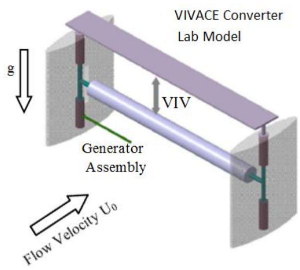

Fig.1, Energy harvesting with cylinder in self-excitement. Technology of vortex induced vibrations for aquatic clean energy VIVACE [1].

Recent investigations have revealed that placing a rigidly mounted geometrical body such as a square cylinder or a plate in the wake of the cylinder may stabilise the system behaviour over a wide range of incoming flow rates and enables the VIV technology to be used at varying flow conditions. With reaching an excited mode of the cylinder-spring-system the vortex shedding frequency ‘locks-in’ to the eigenfrequency of the dynamic system. Further increase of the flow velocity does not lead to a dropout of the excited condition. Furthermore, the oscillation amplitudes increase significantly with an attached body in the cylinder wake.

This leads to a higher energy harvesting capability per stroke. An alteration of the system behaviour takes place by the reduction of the vortex shedding frequency caused by the body in the cylinder wake. The resulting amplitudes are highly sensitive to the gap between both bodies and the dimensions of the downstream body itself. A small non-dimensional gap of g/d (i.e. g/d = 0.5), where *d* is the cylinder diameter and *g* the absolute distance, reveals the highest amplitudes, Fig. 2. Up to now, the aerodynamic principles, which secure the reinforcement of the oscillation amplitude and stabilisation of the excitement mode, have been the topic of only few investigations.

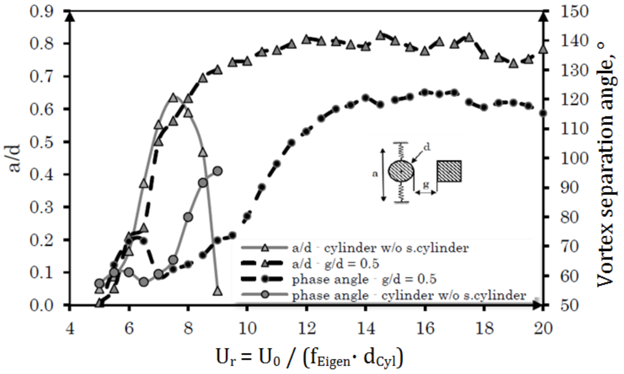

Fig.2, Experimental results of Particle Image Velocimetry (PIV) study. Trend of vibration amplitude (a/d) and vortex separation angle as function of the reduced flow velocity U_r with flow velocity U_0, cylinder-spring eigenfrequency f_{Eigen} and cylinder diameter d_{Cyl} [3].

The lift forces on the cylinder wall, which are highly dependent on the separating angles of the vortices (Fig. 2), are causal for the oscillating movement. Low separation angles result in longer energetisation durations of the vortices and thus higher lift forces. The wake-body represents a damming device and thus has an upstream effect on the separation process of the laminar boundary layer on the cylinder. Recapitulatory, it can be said that the resulting lift forces and thus the efficiency of this cylinder/plate configuration depends on a variety of aerodynamic and geometrical parameters.

The aim of the current study is to deepen the understanding of the acting principles of a cylinder/plate configuration in a steady flow and to provide an informative basis on how to design geometrically beneficial wake-bodies as well as how to manipulate aerodynamic parameters in order to receive the most efficient system. Knowledge on the effect of different geometric and aerodynamic parameters might contribute to an optimal design and consequently to an improvement of the energy efficiency and stability of the oscillating system. For this purpose, the reduction of the originally discussed system from an elastically mounted to a rigidly mounted cylinder simplifies the system and reduces the experimental uncertainties in order to gain knowledge on basic acting principles on the cylinder wall. Moreover, numerical flow simulations and the analysis of the acoustic emissions of a rigidly mounted cylinder in a flow offer a simple and accurate method to characterise the acting forces on the cylinder wall due to separating vortices [7].

The alternately separating vortices that constitute the cause of the lift forces act as a pressure dipole, which induces pressure differences into the surrounding fluid of the cylinder, Fig. 3. These pressure differences propagate at sound velocity and cause Aeolian tones with a peak frequency equal to the vortex shedding frequency (f_{VSF}), Eq. (2).

$$f_{Aeolian}[Hz] = f_{VSF} = {}^{Sr}/_{d_{Cyl.}} \cdot U_0 \qquad (2)$$

Besides the VSF, the acoustic measurements provide further information such as the sound pressure level (SPL), which indicates the magnitude of the acting surface forces, Eq. (3). The vortex shedding frequency as well as the resulting sound pressure level are functions of the distance between cylinder and plate.

$$SPL\,[dB] = 10 \cdot lg\left(\frac{p_{rms}^{\ 2}}{p_0^{\ 2}}\right), \quad p_0 = 2 \cdot 10^{-5} Pa \qquad (3)$$

Where p_{rms} is the root-mean-square value of the sound pressure and p_0 the reference value. The acoustic treatment is advantageous compared to the measurement of wall-forces due to its simplicity and the possibility to carry out measurements with disturbing quantities reduced to its minimum. Furthermore, a variety of response variables can be analysed by simultaneously keeping the experimental volume manageable.

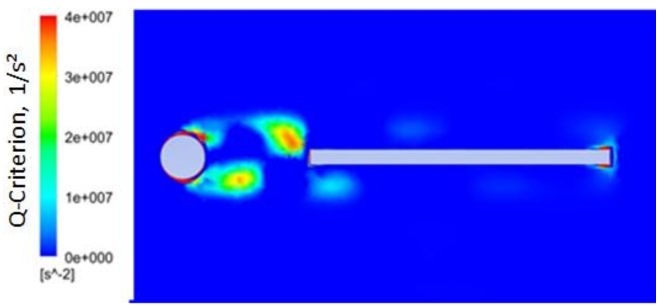

Fig.3, Visualised Q-Criterion. Numerical analysis of a rigidly mounted small-scale cylinder/plate configuration via ANSYS CFD [8].

To enable extensive acoustic investigations of the cylinder/plate configuration, a scaling to small cylinder / plate dimensions has been necessary in order to prevent 3-D effects as well as to treat the configuration in the anechoic chamber that is restricted by limited dimensions of the open jet wind tunnel at the *ISAVE*.

II. Experimental setup

2.1. Test rig & Measurement Facilities

The conduction of the free field measurements of the radiated cylinder/plate interaction noise took place in the open jet wind tunnel in the ISAVE, situated in a 4 m x 6 m anechoic chamber. The nozzle exit is a quadratic section with a lateral length of 0.15 m. The low speed wind tunnel can achieve turbulence intensities as low as 1.5% and Mach numbers as high as 0.12 while maintaining a very low background noise at frequencies above 50 Hz.

A cylinder with d = 3 mm was aligned horizontally at the nozzle exit of the low speed open jet wind tunnel. The cylinder under investigation was fitted with endplates, four times the cylinder diameter and Scruton helices on both sides' outer sections to avoid three-dimensional effects as well as to supress vortex shedding aside from the test region.

A plate with varying geometric dimensions was placed in the wake of the cylinder. Starting at a non-dimensional distance between cylinder and plate of g/d = 1.5 the plate was traversed in streamwise direction up to a distance of g/d = 12 at a traversing speed of 0.4 $mm \cdot s^{-1}$.

The use of a Matlab®-controlled traversing system with minimum steps of 0.1 mm allowed the continuous adjustment of the distance between cylinder and plate. A ¼" ICP condenser microphone was rigid-placed at a distance of 100 mm beneath the cylinder to measure the emitted narrow band spectrum of the dipole noise while altering the cylinder/plate gap. Data acquisition took place by use of Mueller BBM-VAS-PAK acoustic software and a 24-channel frontend at sampling rates of 16 kHz and a resulting frequency resolution of 4 Hz while applying Hanning windowing and overlapping of 36%.

Preliminary investigations into the influence of a variety of different parameters on the noise radiation revealed a set of five characteristic parameters, Table 1. Extensive hot wire measurements were necessary to ensure an accurate description of the turbulence intensity Tu and the open jet flow velocity U_0. The mathematically description of the influence of the parameters on response variables still to be defined, took place by use of a statistical approach. The use of non-dimensional parameters allows a comparison to large-scale applications in future work. The flow speed range under investigation is between 12 m/s and 29 m/s or Reynolds numbers based on the cylinder diameter of 2200 to 5500 respectively. The turbulence intensity of the incoming flow is a flow characteristic considered to have an outstanding relevance. The use of turbulence grids results in a large range of turbulence intensities between 2.4% and 7.8%. The turbulence intensity is considered isotropic.

TABLE 1, Non-dimensional parameters, based on the cylinder diameter d = 3 mm.

Parameter	Unit	Min	Max
Re	[--]	2252	5520
Tu	[%]	2.4	7.8
l_{Plate}	[--]	0.67	4.0
d_{Plate}	[--]	0.17	1.33
$h_{0,\ Displacem.}$	[--]	-0.5	0.5

The definition of plate length and plate thickness bases on the cylinder diameter to provide comparable values to large-scale applications. The vertical displacement between cylinder and plate defines the vertical distance between the centrelines of both bodies. The values of investigation differ in a non-dimensional range of −0.5 to 0.5 based on the cylinder diameter.

2.2. Experimental Methodology

According to the n-permutation, the measurement of the experimental system by varying the parameters (k) of interest in five levels each (n), results in a number of 3125 measurement points, Eq. (4). Applying the statistical approach of Design of Experiments (DoE) reduces the experimental volume and the number of trials to measure (MT) ads up to 43 without relevant loss of information on the system behaviour, Eq. (5).

$$MT_{n-per} = n^k = 3125 \quad (4)$$

$$MT_{DoE} = 2^k + 2 \cdot k + 1 = 43 \quad (5)$$

The Design of Experiments methodology is based on the definition of an experimental space, consisting of a full factorial core, star points that label the upper and lower experimental boundaries and a central point, defined as the experimental adjustment where all parameters are on their intermediary values [2], Fig. 4. Based on this experimental composition of the DoE methodology, the analytical statistics gathers on the population from a subset.

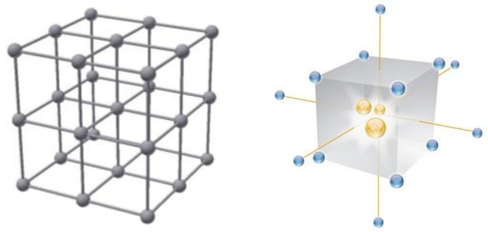

Fig.4, Comparison of a classical grid measurement design (left) and a central composite design with pseudo-orthogonal and rotatable features (right) [5].

Due to its structured composition the presented methodology offers, apart from the remarkable reduction of measurement points, the definition of regression function that describes the response variable (RV) by means of all influencing parameters (IP) in first and second order as well as interdependencies between the influencing parameters, Eq. (6). Analyses of the statistical significance allow the elimination of parameters with impacts on the response variable smaller than the statistical spread.

$$RV_i = f\left\{\sum_{j=1}^{n}\left(\left(IP_j + IP_j^2\right) + \sum_{k=1}^{n}(IP_j IP_{j+k})\right)\right\} \begin{cases} i = 1..4 \\ j = 1..5 \\ k = 1..4 \end{cases} \quad (6)$$

The execution of the experiment had to be divided into three days and the utilisation of *blocking* compensated potential perturbations. The trials of the strategically planned experiment were performed in a randomised order within each block. A randomised sequence secures the reduction or elimination of unknown and uncontrollable disturbing quantities.

III. Experimental Results

Analysing the measured narrow band spectrum while altering the gap between plate and cylinder, results in the definition of different response variables that are evaluated in dependence on the investigated parameters, Table 2.

The first response variable is the non-dimensional distance between cylinder and plate where the sound pressure level starts to rise significantly and Aeolian tones are observed. This variable defines the start of the vortex shedding process at the cylinder ($g/d_{Start,SPE}$). Secondly, the vortex shedding frequency is of high interest to gain knowledge on its system behaviour as a function of the investigated parameters. Division of the VSF by the VSF of a single cylinder in a flow at the same inflow velocity permits a direct comparison between both systems, with and without attached plate ($f_{VSF,Config}/f_{VSF,Single}$). Third, the maximum overall sound pressure level ($OASPL_{Max}$) provides information on the magnitude of acting forces. Finally, the distance at which the acoustic emissions reduce significantly ($d(g/d)_{Start,Stop}$) is of interest due to its indication as marginal distance where the plate influences the vortex separation process at the cylinder. This response variable is defined as the non-dimensional distance between start and end of the sound pressure enhancement (SPE).

TABLE 2, Response variables to be analysed via DoE methodology. Non-dimensional parameters based on cylinder diameter D = 3 mm.

Variable	Unit
$g/d_{Start, SPE}$	[--]
$f_{VSF,Config}/f_{VSF,Single}$	[--]
$OASPL_{Max}$	[dB]
$d(g/d)_{Start,Stop}$	[--]

The Reynolds number under investigation causes in combination with the other investigated parameters vortex shedding frequencies 500 Hz < f_{VSF} < 2000 Hz, Fig. 5. Attaching the plate in the immediate wake of the cylinder supresses the separation of vortices and thus impedes the generation of tonal noise. Exceeding a certain cylinder/plate gap, dependent on the individual parameter levels, the vortex shedding process can take place.

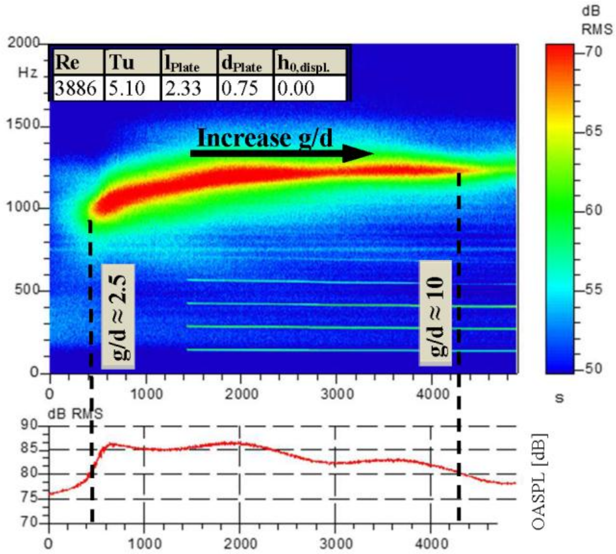

Fig.5, Spectrogram of the SPL over the measurement time, representing the continuous increase of the distance between plate and cylinder. Additional plot of the overall sound pressure level OASPL. Central point trial.

The greater the gap between both geometrical bodies the higher is the VSF until it reaches the VSF, described by the Strouhal law for single cylinders with Strouhal numbers in a range of 0.2 < Sr < 0.21 and 300 < Re < 10^5.

The systematic Design of Experiments approach enables to define regression functions that describe the influence of the different parameters on the defined response variables, Table 3. Analyses of the statistical significance of the parameters and elimination of the non-significant terms result in a high accuracy of these functions.

TABLE 3, Definition of linear combination factors that result in the regression functions to describe the response variables.

$g/d_{Start, SPE}$	f_{Config}/f_{Single}	$OASPL_{Max}$	$d(SPL)_{Max}$
[--]	[--]	[dB]	[--]
-3.69E0	1.48E0	6.5E1	1.43E1
1.75E-3·Re	-8.39E-5·Re	8.86E-3·Re	1.35E-3·Re
-9.57E-8·Re^2	-7.72E-2·Tu	-7.08E-7·Re^2	-5.45E-1·Tu
7.45E-1·Tu	2.36E-3·Tu^2	-4.36E0·Tu	-3.18E0·l_{Plate}
4.81E-1·l_{Plate}	-8.56E-2·l_{Plate}	1.6E-1·Tu^2	-5.54E0·d_{Plate}
-4.89E-2·l_{Plate}^2	1.66E-2·l_{Plate}^2	2.78E0·l_{Plate}	-4.16E0·h_0
2.75E-1·d_{Plate}	-2.28E-1·d_{Plate}	-3.92E-1·l_{Plate}^2	-4.87E0·h_0^2
8.92E-1·h_0	7.19E-2·d_{Plate}^2	-9.33E0·d_{Plate}	-3.29E-4·Re·Tu
-7.61E-1·h_0^2	1.14E-1·h_0^2	3.56E0·d_{Plate}^2	5.19E-1·Tu·l_{Plate}
-1.90E-4·Re·Tu	1.2E-5·Re·Tu	5.84E0·h_0^2	1.63E0·l_{Plate}·d_{Plate}
-4.27E-2·Tu·l_{Plate}	-4.69E-3·l_{Plate}·h_0	8.34E-4·Re·Tu	1.38E0·l_{Plate}·h_0
-3.13E-1·d_{Plate}·h_0			

Carried out validation experiments in form of several measurements at parameter levels deviant to the ones analysed in the DoE analyses result in a good agreement and high accuracy of the analysed system and regression functions. Hence, the mapping of the obtained findings and dependencies of the influencing parameters to large-scale applications for further validation is approvable.

3.1. Plate thickness

Variation of the plate thickness results in a significant change of the response variable. Increasing this parameter causes a reduction of the vortex shedding frequency to lower magnitudes following a primarily linear scaling with slight influences of the quadratic term with opposing trend, Fig. 6. The reduction of the vortex shedding frequency (VSF) originates out of the raised flow resistance induced by the plate and indicates an upstream effect. Due to the rise of the flow resistance, the vortex separation angle in the laminar boundary layer decreases and results in a longer vortex energetisation duration, defined as the time duration between the separation of the boundary layer from the cylindrical wall and the final shed of the fully developed vortex. Vortices of high energy induce strong pressure differences and thus emit a high SPL what indicates high surface forces. Further, it leads to the necessity of a higher cylinder/plate gap, correlated to the vortex formation length, to achieve significant tonal noise.

The vortex formation length (VFL) that describes the required streamwise space needed to enable the full development and cut-off-process of the vortices restricts the minimum distance between cylinder and plate.

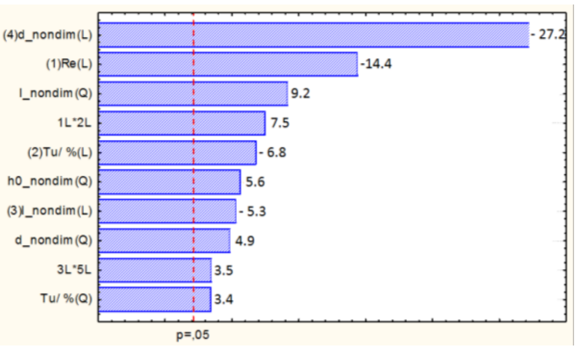

Fig.6, Analyses of the statistical significance of the influencing parameters on the response variable of the VSF. Barrier of statistical significance p = 5 %. Positive values enhance the response variable, negative constrain the response variable.

3.2. Plate length

The plate length was found to have a strong influence on the emitted sound pressure level ($OASPL_{Max}$). A significant rise of the OASPL requires a minimum plate length. Further investigation allocates this dependency as an acoustical phenomenon, not transferable to the aerodynamic system behaviour. At a certain plate length the separated vortices start to impinge on the plate surface and generate, apart from the cylinder surface, a second acoustical source what consequently leads to a rise of the OASPL, Fig. 7. With regard to the aerodynamic performance of the cylinder/plate configuration, the plate length only shows a negligible influence.

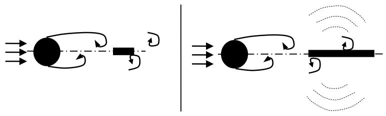

Fig.7, Schematic representation of the aeroacoustic effect of the plate length.

3.3. Turbulence intensity

The start of the vortex shedding process and thus the generation of tonal noise highly depends on the turbulence intensity (Tu). The isotropic turbulence intensity (Tu_{iso}), defined as the quotient of standard deviation (U_{rms}) and mean flow velocity (U_{mean}), Eq. (7), forms a perturbation in the approaching flow of the cylinder and affects the linear boundary layer on the cylinder wall.

$$Tu = \sqrt{\frac{\overline{u'^2+v'^2+w'^2}}{3*(\overline{u}^2+\overline{v}^2+\overline{w}^2)}} \;\rightarrow\; Tu_{iso} = \frac{\sqrt{\overline{u'^2}}}{U_{mean}} = \frac{U_{rms}}{U_{mean}} \quad (7)$$

Where [u’,v’,w’] represent the velocity fluctuation and [u,v,w] the mean velocity components of the velocity vector. The perturbation that acts similar to tripping of the flow results in a low separation angle at the cylinder wall. Thus, high turbulence intensities reduce the vortex shedding frequency but result in low cylinder/plate gaps while the shedding process takes place, Fig. 8. The influence on the VSF is mainly of linear character. Analogue to the variation of the plate thickness, low separation angles lead to vortices of higher energy and accordingly to increased wall-forces. Besides the important linear influence of the turbulence on the minimum distance between cylinder and plate, the interdependency between the Reynolds number and the turbulence has an even higher importance. Either very small or high products of turbulence intensity and Reynolds number effect low start distances. The maximum of this interdependency lies in a region of intermediate values (Tu · Re = 19800 ± 5%).

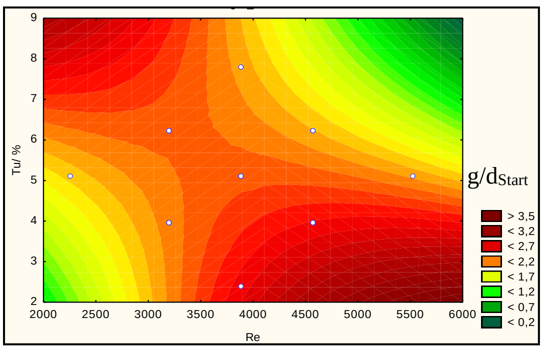

Fig.8, Contour plot, illustrating the influence of Reynolds number and turbulence intensity on the minimum distance between plate and cylinder (g/d_{Start}).

This system behaviour has to be analysed very carefully due to the fact, that the definition of the turbulence intensity bases on the velocity and showed a slight dependence on the velocity magnitude in preliminary investigations.

3.4. Vertical displacement

The vertical displacement of the plate with regard to the cylinder position shows an effect on the cylinder/plate gap similar to the one existing at high turbulence intensities. Moreover, a high vertical displacement influences the vortex formation length (VFL) in a quadratic manner, increases the vortex shedding frequency and reduces the cylinder/plate gap at which the plate exerts influence on the separation process at the cylinder.

In comparison to a horizontal aligned plate, in-line with the cylinder, a high vertical displacement enables the vortex separation at significant lower gaps. Due to the reduced blocking ratio on one side of the cylinder, the vortices are separating at early stages and start to interact with the developing vortices on the opposite side of the cylinder [6]. The fact that the plate is displaced and therefore affects the separation process at higher horizontal distances only with minor forces, leads to a VSF similar to the ones of single placed cylinders, described by the Strouhal law, Eq. (2). This phenomenon is in accordance with the influence on the total affecting distance, which is reduced in a quadratic manner the higher the displacement.

3.5. Reynolds number

Aside from the plate thickness, the Reynolds number represents the main influencing parameter on the vortex shedding frequency. According to the Strouhal law, the flow velocity and thus the Reynolds number influences the VSF proportionally with a linear dependency, Eq. (2).

Analysing the non-dimensional response variable of the VSF, divided by the VSF of a single cylinder reveals a decrease of the response variable with increasing Reynolds number. The underlying effect is reasonable. The higher the Reynolds number the higher the VSF in both cases, with and without plate but in case of an attached plate the rise of the VSF turns out to be disproportional and thus the gap between both divided parameters increases with increasing Reynolds number. With regard to the overall sound pressure level ($OASPL_{Max}$), the Reynolds number represents the main influence. With increasing Reynolds number, the absolute VSF rises and more separated vortices per time unit induce pressure differences in the surrounding fluid of the cylinder. Consequently, the OASPL increases.

IV. Conclusion

Answers to elementary questions regarding the evaluation of the system response as a function of five parameters were found. The key factors of the investigated process were extracted and levels of the different parameters were analysed to deliver an improved performance. Furthermore, key, main and interaction effects were described accurately.

Key factors that affect the aerodynamic performance and in particular the vortex separation angle in the laminar boundary layer on the cylindrical wall of the rigidly mounted cylinder/plate configuration are the Reynolds number (linear), the plate thickness (linear), the vertical displacement (quadratic) and the turbulence intensity (linear plus interdependencies with Reynolds number). The vortex formation length which defines the necessary minimum length to guarantee the development of the vortices (dependent on Reynolds number and turbulence intensity) results in a value at intermediate levels in a range of $g/d \geq 2.2$. This non-dimensional distance defines the lower restriction of the cylinder/plate configuration. The plate length does not represent a significant aerodynamic issue while the plate thickness highly affects the separation angle of the vortices at the cylinder surface. Transferring the reduced rigidly mounted system to the initially regarded oscillating system enables the use of thick but short and aerodynamically optimised plates to increase the resulting oscillation amplitudes by simultaneous reducing the flow resistance of the body. The effects of vertical displacement are expected but in case of an oscillating system of debatable relevance due to the fact that the cylinder strokes are of vertical direction. However, in case of transient oscillation a plate displacement leads to lower cylinder/plate gaps and thus to an increased effect of the plate on the oscillation principle. The implied effect of contracting the affectional distance would be a disadvantage without consequence in case of an oscillating system.

A plate designed with the aim of enforcing the acting lift forces on the cylinder surface due to flow separation would require a high plate thickness ($d_{Plate}/d_{Cylinder} \geq 1.3$), a moderate vertical displacement to enable a transient oscillation at low cylinder/plate gaps ($\pm 0.2 \leq h_0/d_{Cylinder} \leq \pm 0.4$) and moderate to high turbulence intensities ($4.9\% \leq Tu \leq 7.5\%$). The level of vertical displacement and plate thickness contradict each other in case of a rigidly mounted system because the high blocking ratio of the thick plate causes low separation angles that contribute to low separation angles where a vertical displacement acts contrary. Given an elastically mounted system, this conflict resolves due to the vertical movement of the cylinder. The optimal Reynolds number represents a parameter that should be designed in accordance to the eigenfrequency of the cylinder-spring-system.

To verify the found dependencies, further numerical and experimental investigations in the optimum configuration are necessary by applying the defined optimal parameter levels to an elastically mounted system. With regard to a practical application of the cylinder/plate configuration instead of a single oscillating cylinder, energetic considerations are necessary. The attached plate reduces the vortex shedding frequency of the system and thus the strokes per time but the amplitudes of each stroke increases and the system is more stable because of the previously described ‘lock-in’ effect in Section I. Of question is whether the increased amplitudes compensate for the loss in frequency.

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