Faculty of Engineering, Computer and Mathematical Sciences

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The Aeroacoustics of Finite Wall-Mounted Cylinders

Ric Porteous

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the requirements for the degree of
Doctor of Philosophy in engineering.

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Supervisors: *Prof. Ben Cazzolato*
Assoc. Prof. Anthony Zander
Assoc. Prof. Con Doolan
Dr. Danielle Moreau

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School of Mechanical Engineering
The University of Adelaide, 5005
SA, Australia

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Abstract

Community noise is one of the most poorly controlled environmental pollutants. Controlling the noise generated by bluff-body flow can alleviate community noise generated by transportation systems such as aircraft, automobiles and highspeed rail. A foundational example of bluff-body flow is the flow around a square Finite Wall-Mounted Cylinder (FWMC). An FWMC models the major noise producing components of transportation systems, such as landing gear and pantographs, but is also relevant to many facets of engineering including flow around chimney stacks, wind turbine masts, heat exchangers and mountains.

This thesis studies the flow-induced noise generated by square FWMCs with aspect ratios ranging from $0 < L/W < 23$ immersed in boundary layers of thickness $\delta/W = 1.3$ and $\delta/W = 3.7$ at a Reynolds number based on the side width, W, of $Re_W = 1.45 \times 10^4$. The flow-induced noise is measured using single microphone, directivity and phased microphone array measurements. The measured noise is related to the flow around the FWMC with fluctuating wake velocity measurements using a single hot-wire. Surface pressure measurements and oil-film flow visualisation are also conducted to further investigate the flow physics.

The flow-induced noise of FWMCs is characterised in terms of the frequency, magnitude and directivity of the low frequency acoustic tones generated through periodic vortex shedding and the magnitude of the high frequency broadband component. It is found that as the aspect ratio increases, the FWMC transitions through four vortex shedding regimes based on the number of tones in their acoustic spectra. The aspect ratio where the FWMC transitions from one regime to another is dependent on the boundary layer thickness. Within each shedding regime, the noise producing vortex filaments are observed to have different topological structures, corresponding to either a single or multi-cellular wake.

Measurements of the mean and fluctuating aerodynamics using wake velocity and surface pressure measurements provide explanations for the observed acoustic phenomena. In particular, it is discovered that maximum three-dimensional interaction of the free-end downwash with spanwise vortices can disrupt the wake and reduce the flow-induced noise to near background levels, even for aspect ratios as large as $L/W = 7$.

Several numerical models are also developed to aid the analysis. These include a modified version of Curle's Aeolian tone theory suitable for FWMCs and a wake model of higher aspect ratio FWMCs used to study cellular wake vortex topologies.

Finally, phased array source localisation shows that the magnitude of the high frequency broadband noise is closely related to dynamics of the large-scale vortex structures that generate tonal noise. Because of this, broadband noise can be reduced by approximately 30% when the boundary layer is thickened, even when the free-end of the FWMC lies well outside the edge of the boundary layer.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree. I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

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Nomenclature

The majority of the mathematical symbols and abbreviations used in this dissertation are outlined below. In some cases, the same symbol has been used for multiple purposes. These should be unambiguous based on the context of the work in which they appear.

Greek symbols

Γ	Circulation
Π	Boundary layer pressure gradient parameter
α	Temperature coefficient of resistance
β	Base suction coefficient
γ	Ratio of specific heats of air
δ	Boundary layer thickness
δ^*	Displacement thickness
ϵ	Expanded uncertainty, Strength of the van der Pol oscillator
η	Non-dimensional fluid packet dynamics
θ^*	Momentum thickness
κ	von Kármán constant, Non-dimensional viscous coupling constant
λ	Wavelength
μ	Dynamic viscosity of air
ν	Kinematic viscosity
ρ	Density
$\rho(\tau)$	Cross correlation coefficient function
σ	Standard deviation
σ^2	Variance
ϕ	Phase angle
ω	Frequency

Roman symbols

A	The DAMAS A-matrix
B	Number of averaging blocks
B_W	The array beamwidth
C_d	Drag coefficient
C_l	Lift coefficient
C_p	Pressure coefficient

D	Diameter
E	Voltage
F	Force
G	Cross spectral matrix
$G_{xy}(f)$	Cross spectral density
H	Number of data points in each averaging block when performing Welch's method, Hermetian transpose, Boundary layer shape factor
L	Cylinder span
L/W	Aspect ratio
L_p	Overall sound pressure level
M_∞	Free-stream Mach Number
M_0	Number of microphones in the array
N	Number of time record samples
$\mathbf{P}$	Pressure Vector
P	Total pressure
$R_{12}(\Delta z)$	Axial correlation function
Re_W	Reynolds number based on cylinder width, W
St	Strouhal number
$T.I.$	Turbulence intensity
T	Temperature
T_I	Integral time scale
V_∞	Free-stream mean velocity
$\mathbf{W}$	Shading matrix
W	Cylinder width
Y_t	Classical beamforming output at the t^{th} point in the scanning grid
Z	The CLEAN-SC output
a_{it}	Transfer function relating pressure at the i^{th} microphone to the amplitude of the t^{th} source
c_0	Speed of sound
f	Frequency
$\mathbf{h}$	Steering vector
$h_{1/2}$	Half thickness
h_{damp}	Damping ratio
i	Microphone index
j	Imaginary number, $\sqrt{-1}$
k	Wave number
l_f	Formation length
p	Inflation factor of spanwise coupling due to spanwise flow
p_d	Dynamic pressure
q	Fan speed
q_t	Ampltiude of the t^{th} source in a beamforming map
R	Specific gas constant of air
r	Distance
s	Spanwise correlation length parameter
t	Scanning grid index, Time

t_p	Ray propagation time
u	Streamwise velocity
u^+	Velocity in wall units
u_c	Convection velocity
v	Cross-stream velocity
$\mathbf{x}_{Ic}$	Intersection point of the acoustic ray with the velocity shear layer
$\mathbf{x}_t$	Spatial location of the t^{th} position in the scaning grid
x	Streamwise direction (unless otherwise stated)
y	Cross-stream direction (unless otherwise stated)
z	Spanwise direction (unless otherwise stated)
z^+	Spanwise distance in wall units
z_t	Array gain factor at the t^{th} point in the scanning grid

Abbreviations

18WT	18 inch Wind Tunnel
2D	Two-dimensional
3D	Three-dimensional
AWT	Anechoic Wind Tunnel
DAS	Delay-and-Sum
DR	Diagonal removal
FWMC	Finite wall mounted cylinder
HSV	Horseshoe vortex
MDF	Medium density fibreboard
NAH	Near-field acoustic holography
OASPL	Overall sound pressure level
PDF	Probability distribution function
PIV	Particle image velocimetry
POD	Proper orthogonal decomposition
PSD	Power spectral density
PSF	Point Spread Function
R0	Shedding Regime 0
RI	Shedding Regime 1
RII	Shedding Regime 2
RIII	Shedding Regime 3
SPL	Sound pressure level

Operators

$\hat{(.)}$	Estimator
$\overline{(.)}$	Mean operator
bias(.)	Bias operator
Exp(.)	Expectation operator
Prob(.)	Probability distribution function

var(.)	Variance operator
*	Conjugate operator