The University of Adelaide

School of Mechanical Engineering

On the Relation between Fluid Flow over Bluff Bodies and Accompanying Acoustic Radiation

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Thesis for the Degree of Doctor of Philosophy

To the memory of my father and Jurek

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Abstract

The relationship between distinctive characteristic fluid-flow regimes and the sound radiation generated by them has been investigated, over a range of Reynolds numbers, for various single plates and two-plate arrays in nominally two-dimensional flows. In preliminary experiments, the characteristics of flow over single plates with rectangular cross-section and faired leading edges and over tandem arrays of an upstream plate with rectangular cross-section and faired leading edges and a downstream plate of rectangular cross-section were investigated, together with the sound radiation produced. However, the main investigation has been concentrated on single plates of rectangular cross-section with various chord-to-thickness ratios C and on arrays of two plates of rectangular cross-section in tandem having various chord-to-thickness ratios C_1 and C_2 and a range of gaps (with gap-to-thickness ratios G) between them. The range of Reynolds number based on plate thickness t and free-stream velocity U, $Re_t = Ut/v$ (where v is the kinematic viscosity of fluid) covered in the measurements is $3.2 \times 10^3 \leq Re_t \leq 53 \times 10^3$. Spectra of velocity fluctuations in the flow and radiated sound have been measured and their characteristic frequencies related. An attempt has been made to measure force fluctuations on surfaces of the plates in order to relate them to flow characteristics and radiated sound power. Mean and fluctuating pressures associated with the force fluctuations on the plates have also been obtained. The lengths of separation bubbles on long rectangular plates have also been determined. In most cases, the measurements have been complemented by flow-visualisation in a water tunnel to provide additional detailed insight into the flow patterns.

Three flow regimes have been identified for single plates of rectangular cross-section. In the first regime ($1 \leq C \leq 3.13$), shear layers separated from the leading edges form a vortex street downstream of the plate without reattachment to it. Associated force fluctuations on the plate are the main source of acoustic radiation. In the second regime ($3.05 \leq C \leq 9.65$), the separated shear layers reattach intermittently to the streamwise plate surfaces. Vortex formation in the shear layer is the dominant cause of sound radiation but the effect becomes weaker as C increases. In the third regime ($6.52 \leq C \leq 68$), the separated shear layers form closed leading-edge separation bubbles. Weak vortex shedding, with only a small contribution to the sound radiation, occurs only at the trailing edges of the plate. Bistable behaviour of the flow over a plate, with random switching between the regimes, occurs for $C \approx 3$ and $6.52 \leq C \leq 9.65$.

A proposed classification of possible flow regimes for the flow around two plates of rectangular cross-section in tandem has been confirmed experimentally. For small G, the flow in the gap between the plates is isolated from the external flow. When the gap G between the plates is increased to or beyond a critical value (between 2 and 3.5), the shear layers separated from the upstream plate form a von Karman vortex street in the gap before interacting with the downstream plate. Flow and acoustic measurements indicate that this transition is associated with dramatic changes in the flow character.

Generally, acoustic radiation from the various plate configurations is characterised by a combination of two basic types of radiation: dipole radiation resulting from fluctuating forces generated by the fluid flow over the essentially rigid plates, and quadrupole radiation from turbulence in the flow around the plates and in their wakes. The relative contributions of these two types to the resultant radiation depend on the flow regime, the flow speed, the relative magnitudes of force fluctuations generated on the plates immersed in the flow, and the intensity of the free stream turbulence. For some plate configurations, flow characteristics and the resulting acoustic radiation are influenced by edge-tone-type feedback.

Experimental results leading to these conclusions are presented as conformation and clarification of the flow mechanisms involved in the sound generation.

Statement of originality

The material in this thesis is original and has not been submitted previously, in whole or in part, to qualify for any academic award. To the best knowledge of the author, the thesis contains no material previously published by another person except where due reference is made in the thesis.

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.

Antoni Blazewicz

4th August, 2007

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List of symbols

a	radius of pulsating cylinder (chapter 8);
	speed of sound;
b	half-width of exit from contraction;
	half-width of jet;
BR	solid--blockage ratio;
c	plate chord;
	velocity of acoustic wave (chapter 8);
C	chord-to-thickness ratio = c/t;
c_1	chord of upstream plate in an array;
C_1	c_1/t;
c_2	chord of downstream plate in an array;
C_2	c_2/t;
C_D	drag coefficient = $2D/(\rho U^2 S)$ where D = drag and S = cross-section area;
C_f	surface shear stress coefficient;
C_p	specific heat at constant pressure;
C_{pb}	base pressure coefficient = $2p/(\rho U^2)$ where p = base pressure relative to ambient pressure;
C_{p1b}	base pressure coefficient on an upstream plate;
C_{p2a}	face pressure coefficient on a downstream plate;
C_{p2b}	base pressure coefficient on a downstream plate;
d	diameter of a circular cylinder;
D	diameter of a downstream cylinder;
d_1	diameter of a disc;
d_2	diameter of a cylinder in tandem with a disc;
$d_{tapping}$	diameter of a pressure tapping;
f	characteristic shedding frequency;
f_{2a}	frequeny from acoustic pressure spectra corresponding to vortex shedding in Regime 2 (single plates);
f_{2v}	frequency spectra of flow-velocity fluctuations, corresponding to vortex shedding in Regime 2 (single plates);

f_{3a}	frequency from acoustic spectra corresponding to vortex shedding in Regime 3 (single plates);
f_{3v}	frequency from flow spectra corresponding to vortex shedding in Regime 3 (single plates);
f_{5a}	frequency from acoustic spectra corresponding to vortex shedding in Regime 5 (single plates);
f_{5v}	frequency from a flow spectra corresponding to vortex shedding in Regime 5 (single plates);
f_{C1a}	frequency from acoustic spectra corresponding to vortex shedding in Regime C1 (plates in tandem);
f_{C1v}	frequency from flow spectra corresponding to vortex shedding in Regime C1 (plates in tandem);
f_{Ba}	frequency from acoustic spectra corresponding to vortex shedding in Regime C1 (plates in tandem);
f_{Bv}	frequency from flow spectra corresponding to vortex shedding in Regime C1 (plates in tandem);
$f_{m,n}$	cut-off frequency of higher order acoustic mode in pipe;
f_t	frequency of small scale instabilities in vortex-formation region;
f_v	frequency of vortex shedding from a circular cylinder;
f_x	frequency of characteristic peak appearing in Regime 3;
$f'_{m,n}$	cut-off frequency of higher order acoustic mode in pipe adjusted for high velocity;
g	gap between two plates in tandem;
G	g/t;
G_c	critical gap-to-thickness ratio;
h	height of contraction exit;
H	plate half-thickness = $t/2$;
	ratio of boundary layer displacement thickness to momentum thickness;
k	wave number = ω/c;
L	characteristic length of a body
l_f	vortex-formation length;
L_f	l_f/t;
L_R	streamwise velocity-fluctuations at reattachment;

L_X	streamwise integral-scale of turbulence;
M	Mach number;
n	velocity index in acoustic power expression;
p	ambient pressure;
	pressure;
P	pressure amplitude;
p_1	acoustic pressure;
P_1	amplitude of acoustic pressure;
P_2	amplitude of acoustic pressure;
P1	downstream plate in a tandem array;
p_{12}	acoustic pressure;
p_{1b}	base pressure on upstream plate in a tandem array;
p_2	acoustic pressure;
P2	upstream plate in a tandem array;
p_{2a}	face pressure on downstream plate in a tandem array;
p_{2b}	base pressure on downstream plate in a tandem array;
p_t	stagnation pressure;
R	distance from sound source;
Re_c	Reynolds number based on plate chord = Uc/v;
Re_d	Reynolds number based on cylinder diameter = Ud/v;
Re_t	Reynolds number based on plate thickness = Ut/v;
Re_w	Reynolds number based on nozzle width = Uw/v;
s	generalised length of separation bubble
S	s/t;
	total surface area of the reverberation room;
s_{max}	maximum length of separation bubble
s_{min}	minimum length of separation bubble
S_{max}	s_{max}/t;
S_{min}	s_{min}/t;
St	Strouhal number based on plate thickness = ft/U;
St_c	Strouhal number based on plate chord = fc/U;
St_g	Strouhal number based on gap between plates = fg/U;
St_{2a}	Strouhal number from acoustic spectra corresponding to vortex shedding in Regime 2 (single plates);

St_{2v}	Strouhal number from flow spectra corresponding to vortex shedding in Regime 2 (single plates);
St_{3a},	Strouhal number from acoustic spectra corresponding to vortex shedding in Regime 3 (single plates);
St_{3v}	Strouhal number from flow spectra corresponding to vortex shedding in Regime 3 (single plates);
St_{5a},	Strouhal number from acoustic spectra corresponding to vortex shedding in Regime 5 (single plates);
St_{5v}	Strouhal number from a flow spectra corresponding to vortex shedding in Regime 5 (single plates);
St_{cN}	Strouhal number based on Nakamura *et al.* [1991] data;
t	plate thickness;
T	absolute temperature;
T_{60}	reverberation time;
T_t	stagnation temperature;
u	streamwise component of velocity fluctuation;
U	mean free-stream flow velocity;
Uc	convection velocity;
u'	rms streamwise component of velocity fluctuation;
U_{CL}	mean centre-line velocity;
U_{ref}	reference mean velocity;
V	volume of reverberation room;
	mean voltage component (chapter 4);
V'	rms voltage fluctuation;
V_o	voltage output at zero flow;
V_{tube}	voltage signal corresponding to pressure difference $(p_t - p)$;
V_{taps}	voltage signal corresponding to differential pressure.p;
w	nozzle width;
W	acoustic power;
x, y, z	coordinate system for a location in a working section;
x	distance downstream of cylinder (chapter 8);
X	x/t, Y y/t, Z z/t;
X	x/d (chapter 8);

x', y'	coordinate system for hot wire location (chapter 6);
	coordinate system for total pressure tube location in jet for single elliptic-nosed plate (chapter 5);
x_R	mean length of separation bubble;
X_R	x_R/t;
α	phase angle;
	shear parameter;
β	frequency of the fundamental;
	phase difference between acoustic sources;
δ	displacement correction factor;
δ_{BL}	boundary layer thickness;
γ	specific heat ratio for air;
Δp	differential pressure between static tappings in pipe contraction in high-speed rig;
ΔS	$S_{max} - S_{min}$;
ΔZ	δ/b;
λ	wave length of acoustic radiation;
	streamwise vortex spacing;
Λ	λ/t;
ν	kinematic viscosity;
ρ	fluid density;
ϕ	phase angle of acoustic wave;
ϕ_a	power spectral density of acoustic power;
ϕ_f	power spectral density of force fluctuation;
ϕ_p	power spectral density of pressure;
ϕ_v	power spectral density of mean-fluctuation velocity;
φ	phase delay between lift fluctuations;
ω	angular frequency.