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Frequency-domain prediction of broadband trailing edge noise from a blunt flat plate

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ABSTRACT

The aim of this study is to develop an efficient methodology for frequency-domain prediction of broadband trailing edge noise from a blunt flat plate where non-zero pressure gradient may exist in its boundary layer. This is achieved in two ways: (i) by developing new models for point pressure spectra within the boundary layer over a flat plate, and (ii) by deriving a simple formula to approximate the effect of convective velocity on the radiated noise spectrum. Firstly, two types of point pressure spectra-required as input data to predict the trailing edge noise in the frequency domain-are used. One is determined using the semi-analytic (S-A) models based on the boundary-layer theory combined with existing empirical models. It is shown that the prediction using these models show good agreements with the measurements where zero-pressure gradient assumption is valid. However, the prediction show poor agreement with that obtained from large eddy simulation results where negative (favorable) pressure gradient is observed with the boundary layer. Based on boundary layer characteristics predicted using the large eddy simulations, new model for point wall pressure spectra is proposed to account for the effect of favorable pressure gradient over the blunt flat plate on the wall pressure spectra. Sound spectra that were predicted using these models are compared with measurements to validate the proposed prediction scheme. The advantage of the semi-analytic model is that it can be applied to problems at Reynolds numbers for which the empirical model is not available. In addition, it is expected that the current models can be applied to the cases where favorable pressure gradient exists in the boundary layer over a blunt flat plate. Secondly, in order to quantitatively analyze contributions of the pressure field within the turbulent boundary layer on the flat plate to trailing edge noise, total pressure over the surface of airfoil is decomposed into its two constituents: incident pressure generated in the boundary layer without a trailing edge and the pressure formed by the scattering of the incident pressure at the trailing edge. The predictions made using each of the incident and scattered pressures reveal that the convective velocity of turbulence in the boundary layer dominantly affects the radiated sound pressure spectrum, both in terms of the gross behavior of the overall acoustic pressure spectrum through the scattered pressure and in terms of the narrow band small fluctuations of the spectrum through the incident pressure. The interaction term between the incident and the scattered is defined and the incident is shown to contribute to the radiated acoustic pressure through the interaction term. Based on this finding, a simple model to effectively compute the effects of convection velocities of the turbulence on the radiated sound pressure spectrum is proposed. It is shown that the proposed method can effectively and accurately predict the broadband trailing edge noise from the plate with considering both the incident and the scattered contributions.

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Nomenclature

c	chord of flat plate (m)
c_0	speed of sound (ms^{-1})
c_f	skin frictional coefficient
CCV	coefficient of convective velocity
CCV$_t$	coefficient of target convective velocity
CCV$_r$	coefficient of reference convective velocity
$C_1=0.5$, $C_2=1.5$, $C_3=1.1$	constants of Goody model
erf	error function
$E[.]$	operator of expected value
h	flat plate thickness (m)
f	frequency (Hz)
f_i	ith component of force exerted on source region (N)
f_p	function describing the variation of incident pressure in the developing boundary layer
H_p	transfer function from p_i to p
H_q	transfer function from p_i to p_t
H_s	transfer function from p_i to p_s
$\boldsymbol{k}$	vector of wavenumber
$k_c=\omega/U_c$	wavenumber of convective velocity (m^{-1})
$S_0(\omega)$	frequency spectrum p_i on a point in source region
$S(\boldsymbol{y})$	surface of source region
S_{f_p}	acoustic pressure spectral density only for p_i (Pa^2 Hz^{-1})
S_{H_s}	acoustic pressure spectral density only for p_s (Pa^2 Hz^{-1})
SPL	sound pressure level of CCV$_t$ by computing exact formula (dB)
SPL$_a$	sound pressure level of CCV$_t$ by using simple model (dB)
SPL$_a^s$	sound pressure level of CCV$_t$ for only p_s by using simple model (dB)
SPL$_r^s$	sound pressure level of CCV$_r$ for only p_s by computing exact formula (dB)
S_{qq}	frequency–wavenumber spectral density of p_i (Pa/Hz^{-1})
$\hat{S}_{qq}$	frequency–wavenumber spectrum of p_i with frozen turbulence hypothesis (Pa)
t	arrival time of the wave at $\boldsymbol{x}$ (s)
T	large time interval (s)
T'_{ij}	Lighthill's stress tensor
U	moving velocity of source (ms^{-1})
U_c	convective velocity (ms^{-1})
$\omega=2\pi f$	angular frequency (s^{-1})

Greek characters

α_1, α_2	dimensionless coefficients for Corcos's model for the S_{qq}
$\beta^2=1-M^2$	compressibility parameter relative to streamwise mean velocity
δ	boundary layer thickness (m)
δ_*	boundary layer displacement thickness (m)
$\Delta p_s=\overline{p}_{ss}-\overline{p}_{sp}$	pressure jump on $S(\mathbf{y})$
$\kappa=\omega/c_0$	acoustic wavenumber
κ_{const}	von Kraman constant ($=0.41$)
$\mu=\kappa/\beta^2$	ratio of wavenumber to compressibility
$\boldsymbol{v}$	kinematic viscosity (m^2 s^{-1})
ρ_s	density of flow passing through, $S(\boldsymbol{y})$ (kg m^{-3})
ρ_0	density of source region (kg m^{-3})
τ	retarded time (s)
τ_*	wall shear stress (Pa m^{-2})
$'$	measured in the earth-fixed reference frame

Subscripts

0	relative to the source region
i	ith directional component
T.E.	relative to the trailing edge

Superscripts

-	complex amplitude of a Fourier component in frequency domain
∧	complex amplitude of a Fourier component in frequency–wavenumber domain
$*$	complex conjugate
k_s	streamwise directional wavenumber (m^{-1})
k_t	spanwise directional wavenumber (m^{-1})
M	mach number
n_i	ith component of $\mathbf{n}$(y)
$\mathbf{n}$(y)	the unit inward normal vector on $S(\mathbf{y})$
G	green function
p	acoustic pressure (Pa)
p_i	incident pressure on airfoil surface (Pa)
p_s	scattered pressure on airfoil surface (Pa)
p_{sp}	scattered pressure on airfoil surface of pressure side (Pa)
p_{ss}	scattered pressure on airfoil surface of suction side (Pa)
p_t	total pressure on airfoil surface (Pa)
R	mean-flow-corrected distance
Re$_x$	Reynolds number based on x
R_T	ratio of outer to inner boundary layer time scale
R_θ	Reynolds number based on momentum thickness
u_*	frictional velocity (ms^{-1})
V_n	normal velocity of surface, $S(\boldsymbol{y})$ (ms^{-1})
x	distance from L.E to T.E (m)
$\boldsymbol{x}$	the receiving point
$\boldsymbol{y}$	a coordinate vector in source region

Abbreviations

APG	adverse pressure gradient
BTE model	blunt trailing edge model
FPG	favorable pressure gradient
LES	large eddy simulation
PPS	point pressure spectrum
S-A model	semi-analytic model
ZPG	zero pressure gradient
PSD	power spectral density