Optimal spatially fixed and moving virtual sensing algorithms for local active noise control

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Abstract

Local active noise control systems aim to create zones of quiet at specific locations within a sound field. The created zones of quiet generally tend to be small, especially for higher frequencies, and are usually centred at the error sensors. For an observer to experience significant reductions in the noise, the error sensors therefore have to be placed relatively close to an observer's ears, which is not always feasible or convenient. Virtual sensing methods have been proposed to overcome these problems that have limited the scope of successful local active noise control applications. These methods require non-intrusive sensors that are placed remotely from the desired locations of maximum attenuation. These non-intrusive sensors are used to provide an estimate of the sound pressures at these locations, which can then be minimised by a local active noise control system. This effectively moves the zones of quiet away from the physical locations of the transducers to the desired locations of maximum attenuation, such as a person's ears.

A number of virtual sensing algorithms have been proposed previously. The difference between these algorithms is the structure that is assumed to compute an estimate of the virtual error signals. The question now arises as to whether there is an optimal structure that can be used to solve the virtual sensing problem, which amounts to a linear estimation problem. It is well-known that the Kalman filter provides an optimal structure for solving such problems. An optimal solution to the virtual sensing problem is therefore derived in this thesis using Kalman filtering theory. The proposed algorithm is implemented on an acoustic duct arrangement to demonstrate its effectiveness. The presented experimental results indicate that the zone of quiet was effectively moved away from the physical sensor towards the desired location of maximum attenuation.

The previously proposed virtual sensing algorithms have been developed with the aim to create zones of quiet at virtual locations that are assumed spatially fixed within the sound field. Because an observer is very likely to move their head, the desired locations of the zones of quiet are generally moving through the sound field rather than being spatially fixed. For effective control, a local active noise control system incorporating a virtual sensing method thus has to be able to create moving zones of quiet that track the observer's ears. A moving virtual sensing method is therefore developed in this thesis that can be used to estimate the error signals at virtual locations that are moving through the sound field. It is shown that an optimal solution to the moving virtual sensing problem can be derived using Kalman filtering theory. A practical implementation of the developed algorithm is combined with an adaptive feedforward control algorithm and implemented on an acoustic duct arrangement. The presented experimental results illustrate that a narrowband moving zone of quiet that tracks the desired location of maximum attenuation has successfully been created.

Statement of originality

To the best of my knowledge, except where otherwise referenced and cited, all the material that is presented in this thesis is my own original work and has not been published previously for the award of any other degree or diploma in any university or other tertiary institution. If accepted for the award of the degree of Doctor of Philosophy in Mechanical Engineering, I consent that this thesis be made available for loan and photocopying.

Cornelis D. Petersen

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Nomenclature

Signals

d_p	physical primary disturbance
d_v	virtual primary disturbance
e_p	physical error signal
e_v	virtual error signal
r_p	physical filtered-reference signal
r_v	virtual filtered-reference signal
s	disturbance source signal
u	control signal
x	feedforward reference signal
x_{fb}	intrinsic feedback signal
y_p	physical secondary disturbance
y_v	virtual secondary disturbance
z	state
ε_p	physical innovation, physical output error
ε_v	virtual innovation, virtual output error
ρ	state estimation error

Transfer paths and impedances, controllers and filters

C	feedback controller
G	arbitrary plant or system
G_{ci}	co-inner factor of G, $G_{ci}G_{ci}^* = I$
G_{co}	co-outer factor of G, $G_{co}G_{co}^* = GG^*$
G_i	inner factor of G, $G_i^*G_i = I$
G_o	outer factor of G, $G_o^*G_o = G^*G$
$G_{ci}^{\perp}$	co-inner factor perpendicular to G_{ci}, $G_{ci}^{\perp}G_{ci}^{\perp *} = I$ and $G_{ci}G_{ci}^{\perp *} = 0$
$G_i^{\perp}$	inner factor perpendicular to G_i, $G_i^{\perp *}G_i^{\perp} = I$ and $G_i^{\perp *}G_i = 0$

G_{ps}	physical primary transfer path
G_{pu}	physical secondary transfer path
G_{xs}	detector transfer path
G_{xu}	intrinsic feedback path
G_{vs}	virtual primary transfer path
G_{vu}	virtual secondary transfer path
H	filter
W	feedforward controller
Z_{ps}	physical primary transfer impedance
Z_{pu}	physical secondary transfer impedance
Z_{xs}	detector transfer impedance
Z_{xu}	intrinsic feedback impedance
Z_{vs}	virtual primary transfer impedance
Z_{vu}	virtual secondary transfer impedance

Symbols

f	frequency (Hz)
h	physical sensor weight
n	time index
x_p	spatial location of physical sensor/primary source
x_s	spatial location of secondary source
x_v	spatial location of virtual sensor
w	control filter coefficient
z	complex variable in the z-transform, unit shift forward operator
I	number of control filter coefficients
J	cost function
K	number of feedforward reference sensors
L	number of control sources
M_p	number of physical sensors
M_v	number of virtual sensors
N	order of state-space system
P	covariance of state estimation error, inverse correlation matrix
Q	covariance of process noise
R	covariance of measurement noise
S	cross-covariance between process and measurement noise
α	convergence coefficient (normalised filtered-x LMS algorithm)
δ	regularisation parameter (filtered-x RLS algorithm)
ϵ	regularisation parameter (normalised filtered-x LMS algorithm)

η	attenuation (dB)
λ	forgetting factor (filtered-x RLS algorithm)
μ	convergence coefficient (filtered-x LMS algorithm)
ω	angular frequency (rad/s)
σ	variance
Π	covariance of states
$*$	discrete-time convolution
$\otimes$	Kronecker matrix product
$\mathbb{R}$	field of real numbers
$\mathbb{C}$	field of complex numbers
$\in$	belong to
$\perp$	perpendicular to
$\forall$	for all
$\square$	end of proof
$\sim$	defined by
$\triangleq$	defined as
$\approx$	approximately
$\simeq$	similar or equivalent
$\mathcal{RH}^{m\times n}$	set of all all rational $m \times n$ transfer function matrices with real coefficients and excluding singularities on the unit circle
$\mathcal{RH}_{\infty}^{m\times n}$	set of all asymptotically stable rational $m \times n$ transfer functions matrices with real coefficients
$\mathcal{RH}_{p}^{m\times n}$	set of all all rational proper $m \times n$ transfer function matrices with real coefficients
${}^{10}\log[\cdot]$	logarithm operator with base 10
$\mathrm{var}[\cdot]$	variance operator
$\mathrm{E}[\cdot]$	expectation operator
$[\cdot]^*$	adjoint operator
$[\cdot]_+$	causality operator
$[\cdot]_-$	non-causality operator
$\|\cdot\|_2$	H_2-norm operator
$\lvert\cdot\rvert$	magnitude operator
$\angle$	phase operator

Matrix conventions

a	scalar
$\mathbf{a}$	column vector
$\mathbf{a}^{\mathrm{T}}$	transpose of $\mathbf{a}$
$\mathbf{a}^{\mathrm{H}}$	complex conjugate transpose of $\mathbf{a}$
$\mathbf{A}$	matrix
$\mathbf{A}^{\mathrm{H}}$	complex conjugate transpose of $\mathbf{A}$
$\mathbf{A}^{\mathrm{T}}$	transpose of $\mathbf{A}$
$\mathbf{A}^{-1}$	inverse of $\mathbf{A}$
$\mathbf{A}^{-\mathrm{H}}$	inverse of $\mathbf{A}^{\mathrm{H}}$
$\mathbf{A}^{-\mathrm{T}}$	inverse of $\mathbf{A}^{\mathrm{T}}$
$\mathbf{A}^{\dagger}$	generalised or pseudo-inverse of $\mathbf{A}$
$\mathbf{I}$	identity matrix
$\mathrm{tr}(\mathbf{A})$	trace of $\mathbf{A}$
$\kappa(\mathbf{A})$	condition number of $\mathbf{A}$

Abbreviations

AD	analogue to digital
ANC	active noise control
BPF	blade passage frequency
DA	digital to analogue
DARE	discrete-time algebraic Ricatti equation
FIR	finite impulse response
IIR	infinite impulse response
IMC	internal modal control
LMS	least mean-squares
LQG	linear quadratic gaussian
MIMO	multiple input multiple output
NMSV	normalised mean-square virtual output error
PEM	prediction error method
PO-MOESP	past output multi-variable output error state space
RLS	recursive least squares
SISO	single input single output
SMI	subspace model identification
SNR	signal to noise ratio
VAF	variance accounted for