A study of tyre cavity resonance noise mechanism and countermeasures using vibroacoustic analysis

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Nomenclature

J_m	Bessel function of the first kind, order *m*
Y_m	Bessel function of the second kind, order *m*
f_i	*i*th modal frequency
f_V	the vertical mode of the tyre cavity frequency
f_H	the fore-aft mode of the tyre cavity frequency
f_{lm}	tyre tread / cylinder shell natural frequency
i	the order of cavity resonance mode
l	torus length
m,n,l	mode order integer
A_{mn}	coefficient for Bessel function of the first kind
B_{mn}	coefficient for Bessel function of the second kind
f	frequency in Hertz
t	time in second
A_r, A_θ, A_z	coefficients of cylinder shell mode shapes
R_m	tyre cavity mid-radius
R	cylinder shell mid-radius
R_i	the inner radius of the tyre cavity
R_o	the outer radius of the tyre cavity
h	cylinder shell thickness
ν	Poisson's ratio
Ω_f	cylinder shell natural frequency
ρ_s	cylinder shell density

ϕ	cylinder shell mode shape function
Φ	phase angle
$\mathbf{a}$	the acoustic modal amplitude vector (Nx1)
$\mathbf{b}$	the structural modal amplitude matrix (Mx1)
$\boldsymbol{\varphi}^{T}$	transpose of acoustic mode shape vector
$a_n(\omega)$	n^{th} complex amplitudes of acoustic mode shape
C_{mn}	element of a coupling coefficient matrix (MxN)
ρ_o	air density
$\alpha_n(\omega)$	cavity resonance terms
T_{60}	60 dB reverberation time
$\mathbf{Z}_a$	acoustic impedance matrix (NxN);
$\mathbf{q}$	generalized modal acoustic source strength vector (1xN)
α	sound absorption coefficient
E_1	Mean vibrational energy of subsystem 1
η_1	modal densities of subsystem 1 (tyre)
η_{12}	coupling loss factor from subsystem 1 to 2
Π_1	power input to subsystem 1
$\mathbf{I}$	Identity matrix (MxN)
M_1	mass of subsystem 1
$\langle \overline{p_2^2} \rangle$	time and space-averaged pressure square of subsystem 2 or cavity
V	volume of the enclosure or cavity
P	total edge length or circumference
k_1	structural wave number in the axial direction
n_1	modal density of type 1
Π	sound power

$\left\langle \overline{v_1^2} \right\rangle$	time and space-averaged mean-square vibration velocity of the structure
f_R	'plane stress' ring frequency in Hertz
f_r	'plane strain' ring frequency in Hertz
F_0	magnitude of point force
n_n	normalised modal density
f_0	centre frequency of a frequency band
$\mathbf{D}_d$	dynamic matrix of the tyre cavity
$\mathbf{F}_k$	vector of forces arising from subsystem k
$< >$	spatial average
χ	roots of the Bessel's characteristic equation
ωl	upper limit of frequency band
$H(f)$	frequency response function
$X(f)$	input of the system in frequency domain
$H2(f)$	estimator of the frequency response functions
$S_{xx}(f)$	auto spectral density in the frequency domain of $X(t)$
$\gamma(\omega)^2$	coherence function
$X(t)$	input of the system in time domain
η_s	loss factor due to structural damping loss
σ_m	air flow resistivity
h_m	polyfelt trim thickness
η_j	loss factor due to structural boundary damping
k	wave number
ω	circular frequency in radian/second
c	speed of sound at 343 m/s

p	sound pressure
φ	acoustic mode shape function
r,θ,z	cylindrical coordinate for tyre cavity and cylinder shell
u,v,w	cylinder shell displacement directions
w_r	radial cylinder shell deformation
u_z	axial cylinder shell deformation
W	toroid @ tyre cavity width
v_θ	circumferential cylinder shell deformation
L	cylinder shell @ tyre tread width
E	Young's modulus
B_{ml}	normalised cylinder shell mode shape coefficient
U_{mnl}	normalisation factor
V_{mnl}	normalised mode shape coefficient
N_θ, N_z	limit number of cylinder shell mode shape terms
$\mathbf{I}$	unit matrix (MxN)
$\boldsymbol{\phi}^T$	transpose of structural mode shape vector
$b_m(\omega)$	n^{th} complex amplitudes of structural mode shape
g_m	generalised modal force
q_n	generalised acoustic strength
$\beta_m(\omega)$	structural resonance terms
η	damping loss factor
$\mathbf{Y}_S$	structural mobility matrix (MxM)
$\mathbf{g}$	generalised modal force vector (1xM)
E_2	Mean sound pressure wave energy of subsytem 2
η_2	modal density of subsystem 2 or cavity

η_{21}	coupling loss factor from subsystem 2 to 1
S	cylinder shell or tyre tread surface area
S_l	circumferential length of the cylinder shell
M_2	mass of subsystem 2
$\langle \overline{v_1^2} \rangle$	time and space-averaged velocity square of subsystem 1
A	total surface area
k_2	structural wave number in the circumferential direction
n_{II}	modal density of type 2
σ	radiation efficiency
W	axial width of tyre cavity
f_c	critical frequency in Hertz
P_{in}	input power
L	axial width of tyre tread or cylinder shell
ω_r	'plane strain' ring frequency in radian
ω_R	'plane stress' ring frequency in radian
$\mathbf{F}$	vector of external forces applied directly to the cavity
$\mathbf{D}_{dir}^{(k)}$	direct field dynamic stiffness matrix for subsystem k
$\mathbf{F}_{rev}^{(k)}$	reverberant field force vector
$\omega 2$	lower limit of frequency band
$Y(f)$	ouput of the system in frequency domain
$H1(f)$	estimator of the frequency response functions
$S_{xy}(f)$	cross spectral density in the frequency domain of $X(t)$ and $Y(t)$
$S_{yy}(f)$	auto spectral density in the frequency domain of $Y(t)$
$S_{yx}(f)$	cross spectral density in the frequency domain of $Y(t)$ and $X(t)$
$Y(t)$	ouput of the system in time domain

η_{rad}	loss factor due to acoustic radiation damping
ρ_m	polyfelt trim density
κ, γ, d	air flow resistivity constants
Superscript	
*	complex conjugate
T	transpose
‘	first derivative
-	time average

Abbreviations

SEA statistical energy analysis

FE finite element

@ also known as

EMA experimental modal analysis

rms root mean square