EMS-TECH INC.

23073 - Modified Discharge Boom 04155/05050
VORTEX SHEDDING

INPUTS

Member: PIPE 406.4 O.D.x 9.5 wall thk

D =	16		Pipe Diameter, in
I =	560.71	in⁴	
S =	70.09	in³	
w =	62.48	lb/ft	
μ =	0.0135	lb*sec²/in²	
E =	2.90E+07	lb/in²	

	Mode 1 (fixed-hinged)	Mode 1 (fixed-fixed)	Mode 2 (fixed-hinged)
A =	15.4	22.4	50

(Harris, C.M. - Shock and Vibration Handbook 5th Edition pg 1.13)

Op. Wind = 20 m/s, q = 240 N/m²

St. Wind = 63 m/s, q = 2381 N/m²

L =	569	Length of Unsupported Structure, in
t =	0.37	Wall Thickness, in
A =	18.361	in²
β =	0.01	Dampening Ratio (ζ) (Supplment to the National Building Code of Canada 1990, Pg 146, 22. Steel frames)
H =	14.45	Height of the Structure, m

Lu = 1 / 3 * L — For Mode 2

OUTPUTS

$\omega_0 = A*(EI/(\mu L^4))^{0.5}$ Natural Frequency, rad/sec (Harris, C.M. - Shock and Vibration Handbook 5th Edition pg 1.13)

where E = Young's Modulus, lb/in²
I = Area Moment of Inertial of Beam Cross Section, in⁴
L = Lenth of Beam, in
μ = mass per unit length of beam, lb-sec²/in²
A = Coefficient from Table

$V_h = (1 / S)* \omega_0 * D$ Mean Wind Speed, m/s (Supplment to the National Building Code of Canada 1990, Pg 149, Eq. 11)

where S = Strouhal Number (Supplment to the National Building Code of Canada 1990, Pg 149, Eq. 11a, 11b, 11c)
D = Diameter, in
ω_0 = Angular Natural Frequency (No Axial Force), Hz

$F_L = C_l/(\lambda^{0.5}*(\beta-C_s(\rho D^2)/M)^{0.5})*q_h*D$ Static Force Approximation From Dynamic Vortex Effect, N/m
(Supplment to the National Building Code of Canada 1990, Pg 150, Eq. 12)

where C_l = Constant 1
λ = Aspect Ratio (H/D) = 35.57
β = Critical Dampening Ratio as Defined for Equation (9) If ; $C_s(\rho D^2/M) > \beta$ Then Large Amplitued Motions, Up to 1 x D, May Result
C_s = Constant 2
ρ = Density of Air = 1.2 kg/m³
D = Diameter, m
M = Average Mass per Unit Length Over the Top One-Third of the Structure, kg/m
q_h = Velocity Pressure Corresponding to V_H. Where V_H is in m/s = $0.6*V_h^2$ in Pa

No Axial Force (Non-Operating, Parked In Bolster)

Mode 1 (fixed-hinged)	Mode 1 (fixed-fixed)	Mode 2 (fixed-hinged)
ω_0 = 52.21 rad/sec	ω_0 = 75.95 rad/sec	ω_0 = 169.52 rad/sec
ω_0 = 8.31 Hz	ω_0 = 12.09 Hz	ω_0 = 26.98 Hz
ω_0*D^2 = 1.372 m^2/sec	ω_0*D^2 = 1.996 m^2/sec	ω_0*D^2 = 4.456 m^2/sec
V_h = 16.89 m/s **Bad**	V_h = 24.56 m/s **Bad**	V_h = 54.82 m/s **Bad**
Vel. Pressure, q_H = 171.08 N/m^2	Vel. Pressure, q_H = 361.95 N/m^2	Vel. Pressure, q_H = 1803.42 N/m^2
C_1 = 3.00	C_1 = 3.00	C_1 = 3.00
C_2 = 0.6	C_2 = 0.6	C_2 = 0.6
$C_s(\rho D^2/M)$ = 0.0013 **OK**	$C_s(\rho D^2/M)$ = 0.0013 **OK**	$C_s(\rho D^2/M)$ = 0.0013 **OK**
F_L = 374.51 N/m	F_L = 792.36 N/m	F_L = 3947.91 N/m
f / ω_0 = 1.00	f / f_0 = 1.00	f / f_0 = 1.00
|H(f)| = 50 DMF (Figure 7)	|H(f)| = 50 DMF (Figure 7)	|H(f)| = 50 DMF (Figure 7)
UDL = 18.73 kN/m	UDL = 39.62 kN/m	UDL = 197.40 kN/m
UDL= 18.73 kN/m	UDL= 39.62 kN/m	UDL= 197.40 kN/m
Moment = 489.02 kN-m	Moment = 1034.62 kN-m	Moment = 1718.31 kN-m
Stress = 425.77 MPa	Stress = 900.80 MPa	Stress = 1496.06 MPa

Unloaded Cylinder, Luffing Structrue Load (Supported in Bolster, Storm Wind)

Mode 1 (fixed-hinged)	Mode 1 (fixed-fixed)	Mode 2 (fixed-hinged)
ω_0 = 8.33 Hz	ω_0 = 12.11 Hz	ω_0 = 27.00 Hz
ω_0*D^2 = 1.375 m^2/sec	ω_0*D^2 = 2.001 m^2/sec	ω_0*D^2 = 4.459 m^2/sec
V_h = 16.92 m/s **Bad**	V_h = 24.61 m/s **Bad**	V_h = 54.85 m/s **Bad**
Vel. Pressure, q_H = 171.82 N/m^2	Vel. Pressure, q_H = 363.53 N/m^2	Vel. Pressure, q_H = 1805.38 N/m^2
C_1 = 3.00	C_1 = 3.00	C_1 = 3.00
C_2 = 0.6	C_2 = 0.6	C_2 = 0.6
$C_s(\rho D^2/M)$ = 0.0013 **OK**	$C_s(\rho D^2/M)$ = 0.0013 **OK**	$C_s(\rho D^2/M)$ = 0.0013 **OK**
F_L = 376.15 N/m	F_L = 795.81 N/m	F_L = 3952.21 N/m
f / f_0 = 1.00	f / f_0 = 1.00	f / f_0 = 1.00
|H(f)| = 50 DMF (Figure 7)	|H(f)| = 50 DMF (Figure 7)	|H(f)| = 50 DMF (Figure 7)
UDL = 18.81 kN/m	UDL = 39.79 kN/m	UDL = 197.61 kN/m
UDL= 18.81 kN/m	UDL= 39.79 kN/m	UDL= 197.61 kN/m
Moment = 491.15 kN-m	Moment = 1039.12 kN-m	Moment = 1720.18 kN-m
Stress = 427.62 MPa	Stress = 904.72 MPa	Stress = 1497.69 MPa

Effect of Axial Load (Harris, C.M. - Shock and Vibration Handbook 5th Edition pg 7.21)

$\omega_n = \omega_0 (1\pm\alpha^2/n^2)^{0.5}$ Natural Frequency with Axial Force, Hz
$\alpha = FL^2/EI\pi^2$
ω_0 = Natural Frequency with no axial force, Hz
n = Mode Number

F = 32710 lbs, Unloaded Cylinder, Luffing Structure Load (+ tensile force - compressive force)
α = 0.066

F = 249538 lbs, Dead Load Only (+ tensile force - compressive force)
α = 0.504

F = 297872 lbs, DL + Normal Operating Materail (+ tens - comp)
α = 0.601

Single Degree of Freedon (SDOF) Dynamnic Modification Factor (DMF) from "The Nature of Wind Loads and Dynamic Response" Boggs and Dragovich 2006 - Figure 7

Max Non-Operating Wind = 63 m/s

ω_0*D^2	>0.75	<0.75 and >0.5	<0.5
	Yes	No	No
ω_0 =	31.00	48.65	25.84
ω_0*D^2 =	5.12	8.03	4.27
V_h =	63.00	63.00	63.00

Max Operating Wind = 20 m/s

ω_0*D^2	>0.75	<0.75 and >0.5	<0.5
	Yes	No	No
ω_0 =	9.84	13.38	8.20
ω_0*D^2 =	1.63	2.21	1.35
V_h =	20.00	20.00	20.00

Effect of Axial Load (Dead Load Only <Operating Case>)

Mode 1 (fixed-hinged)	Mode 1 (fixed-fixed)	Mode 2 (fixed-hinged)
ω_n = 9.30 Hz	ω_n = 13.53 Hz	ω_n = 27.82 Hz
ω_n*D^2 = 1.537 m^2/sec	ω_n*D^2 = 2.235 m^2/sec	ω_n*D^2 = 4.595 m^2/sec
V_h = 18.91 m/s **Bad**	V_h = 27.50 m/s **OK**	V_h = 56.53 m/s **OK**
Vel. Pressure, q_H = 214.45 N/m^2	Vel. Pressure, q_H = 453.72 N/m^2	Vel. Pressure, q_H = 1917.72 N/m^2
C_1 = 3.00	C_1 = 3.00	C_1 = 3.00
C_2 = 0.6	C_2 = 0.6	C_2 = 0.6
$C_s(\rho D^2/M)$ = 0.0013 **OK**	$C_s(\rho D^2/M)$ = 0.0013 **OK**	$C_s(\rho D^2/M)$ = 0.0013 **OK**
F_L = 469.46 N/m	F_L = 993.24 N/m	F_L = 4198.12 N/m
f / f_0 = 1.00	f / f_0 = 0.73	f / f_0 = 0.35
|H(f)| = 50 DMF (Figure 7)	|H(f)| = 2.3 DMF (Figure 7)	|H(f)| = 1.2 DMF (Figure 7)
UDL = 23.47 kN/m	UDL = 2.28 kN/m	UDL = 5.04 kN/m
UDL= 23.47 kN/m	UDL= 2.28 kN/m	UDL= 5.04 kN/m
Moment = 612.99 kN-m	Moment = 59.66 kN-m	Moment = 43.85 kN-m
Stress = 533.71 MPa	Stress = 51.94 MPa	Stress = 38.18 MPa

Effect of Axial Load (Dead Load + Normal Operating Material <Operating Case>)

Mode 1 (fixed-hinged)	Mode 1 (fixed-fixed)	Mode 2 (fixed-hinged)
ω_n = 9.70 Hz	ω_n = 14.10 Hz	ω_n = 28.17 Hz
ω_n*D^2 = 1.601 m^2/sec	ω_n*D^2 = 2.329 m^2/sec	ω_n*D^2 = 4.653 m^2/sec
V_h = 19.70 m/s **Bad**	V_h = 28.66 m/s **OK**	V_h = 57.25 m/s **OK**
Vel. Pressure, q_H = 232.88 N/m^2	Vel. Pressure, q_H = 492.71 N/m^2	Vel. Pressure, q_H = 1966.28 N/m^2
C_1 = 3.00	C_1 = 3.00	C_1 = 3.00
C_2 = 0.6	C_2 = 0.6	C_2 = 0.6
$C_s(\rho D^2/M)$ = 0.0013 **OK**	$C_s(\rho D^2/M)$ = 0.0013 **OK**	$C_s(\rho D^2/M)$ = 0.0013 **OK**
F_L = 509.80 N/m	F_L = 1078.60 N/m	F_L = 4304.44 N/m
f / f_0 = 1.00	f / f_0 = 0.70	f / f_0 = 0.35
|H(f)| = 50 DMF (Figure 7)	|H(f)| = 2 DMF (Figure 7)	|H(f)| = 1.2 DMF (Figure 7)
UDL = 25.49 kN/m	UDL = 2.16 kN/m	UDL = 5.17 kN/m
UDL= 25.49 kN/m	UDL= 2.16 kN/m	UDL= 5.17 kN/m
Moment = 665.67 kN-m	Moment = 56.33 kN-m	Moment = 44.96 kN-m
Stress = 579.57 MPa	Stress = 49.05 MPa	Stress = 39.15 MPa