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Fan Foundation Block Dynamic (Vibration) Analysis

**NOTE – all calculations reference ACI 351.3R-04*

Basic Design Parameters

Centrifugal fan model = Howden 9825 AFS 6146 DWDI
Balanced to ISO G2.5
Impeller = 7,845 lbs (WK^2 = 70,407 lb-ft^2)
Shaft = 12,645 lbs (WK^2 = 3,111 lb-ft^2)
Motor = 2,000 HP, 894 RPM, 12,790 lbs
Bearings = approx. 1,300 lbs each

Dynamic load (provide by Howden) = 7,031 lbs (vertical and horizontal) in plane of rotation.

Main block = 37' long x 15' wide x 5' thick
Pedestal 1 (supports motor / bearing) = 8.58' x 11.92' x 5.94' tall
Pedestal 2 (supports bearing) = 8.58' x 5' x 5.94' tall

Center of impeller load located centrally on 15' side, but 22.44' from edge on 37' side, and 12.43' above bottom of main mat.

Section 3.2.2.1 – Dynamic load due to unbalanced mass

Dynamic load provided by Manufacturer (3.2.2.1a)
Howden has provided the following dynamic loads for the impeller:

- D_x = 7,031 lbs
- D_y = 7,031 lbs
- D_z = 2,970 lbs

**NOTE – analysis will be based on Howden dynamic loads, but other methods will be shown below for reference.*

Machine unbalance provided by Manufacturer (3.2.2.1b)
This method does not directly use "Q" – instead it uses the eccentricity of the rotating mass (lbm = lbf).

Q = eω
(0.1 in/s) = (e)(93.6 rad/s)
e = 0.1 / 93.6 = 0.00107"

Equation 3-3:
$F_o = m_r e_m \omega_o^2 S_f$ / 12 = (20,490)(0.00107")(93.6^2)(2) / 12 = 32,013 lbs

- dynamic force (lbf)
- m_r = 20,490 lbm
- e = 0.00107"

- ω_o = 93.6 rad/s
- S_f = 2

**NOTE – even if the service factor is taken as 1, the calculated dynamic force (F_o) is still over twice as much as the value provided by Howden. It's unclear as to why the Howden dynamic load is so much lower. If only the impeller was considered (7,845 lbm), and a service factor of 1.15 is used, this results in F_o = 7,037 lbf. It's also possible that although the balancing is rated to ISO G2.5, the actual balancing exceeds that criteria, and Howden has actual testing data that confirms a lower dynamic load.*

Machine unbalance meeting industry criteria (3.2.2.1c)
Howden has stated that the impeller assembly has been dynamically balanced to ISO G2.5. Table 3.1 indicates that for a balance quality grade G2.5 that the product of eω (Q) is 0.1 in/s.

Equation 3-4:
$F_o = m_r Q \omega_o S_f / 12$ = (20,490)(0.1)(93.6)(2) / 12 = 31,964 lbs

- F_o = dynamic force (lbf)
- m_r = rotating mass (lbm) = impeller (7,845 lbm) + shaft (12,645 lbm) = 20,490 lbm
- Q = 0.1 in/s (Table 3.1)
- ω_o = circular operating frequency of machine = (894 rpm * 2π / 60) = 93.6 rad/s
- S_f = 2

**NOTE – this compares reasonably well with the method shown above. The same reasoning applies to the difference of the Howden dynamic loads.*

Machine unbalance by empirical method (3.2.2.1d)
Equation 3-6:
$F_o = W_r f_o / 6{,}000$ = (20,490 lbf)(894 rpm) / 6,000 = 3,053 lbf

- F_o = dynamic force (lbf)
- W_r = rotating weight = 20,490 lbf
- f_o = operating speed = 894 rpm

**NOTE – this is roughly 1/10 of the other two methods listed above. Something has to be wrong with either equation 3-3/3-4 or 3-6. Likely a units issue somewhere.*

Section 3.3 – Dynamic soil properties
Initial assumptions:

- Poisson's ratio, v = 0.45
- Dynamic Shear Modulus, G = 10 k/in^2 = 1,440,000 lb/ft^2
- Unit weight of soil = 120 pcf
- Damping, β_m = 5%
- Cohesive soil

**NOTE – these soil values have been assumed. Geotechnical engineer will provide more reliable values. I will refine design based on pending soils report.*

Section 3.4 – Vibration performance criteria

Per the bid documents, the maximum vibration velocity amplitude of the motor pedestals under full load is 0.2 in/s.

**NOTE - it's unclear if this applies to the vertical or horizontal direction, or if it's for either direction.*

Howden recommends that the foundation frequency should be a minimum of 1.5 times the operating frequency of the fan.

**NOTE - preliminary data demonstrates that this requirement will be very difficult to achieve, based on the assumed soil conditions. The operating frequency is 14.9 Hz, so that means a natural frequency of 22.4 Hz is required for the foundation.*

Section 4.2 – Impedance provided by supporting media

Equivalent radius calculation

Translation, $R = \sqrt{(ab / \pi)} = \sqrt{((37 * 15) / \pi)} = 13.29'$

- $a = 37'$
- $b = 15'$

**NOTE - Rocking and torsion impedance has been ignored for this calculation. This is also the case for the Machine Foundation Wizard in Staadpro Foundation Advanced.*

Dimensionless frequency

Equation 4-11:

$a_o = (R)(\omega_m)(\sqrt{(\rho / G)}) = (13.29)(93.6)(\sqrt{(3.73 / 1{,}440{,}000)}) = 2.002$

- R = equivalent foundation radius = 13.29'
- ω_m = circular frequency of motion = (894 RPM / 60)(2π) = 93.6 rad/s
- ρ = soil mass density = 120 lb/ft^3 / 32.2 ft/s^2 = 3.73 $lbf\text{-}s^2/ft^4$
- G = dynamic shear modulus = 1,440,000 lb/ft^2

Veletsos Method (Section 4.2.1.2)

For this method, impedance is dependent on frequency.

Table 4.1:

- Poisson's ratio, $v = 0.45$
- $\alpha_1 = 0.600$
- $\gamma_1 = 0.103$ (by interpolation)
- $\gamma_2 = 0.235$ (by interpolation)
- $\gamma_3 = 0.120$ (by interpolation)
- $\gamma_4 = 0.821$ (by interpolation)

Parameter $\chi_v = [(\gamma_1)(\gamma_2 a_o)^2] / [1 + (\gamma_2 a_o)^2] = 0.0187$

Parameter $\psi_v = [(\gamma_1\gamma_2)(\gamma_2 a_o)^2] / [1 + (\gamma_2 a_o)^2] = 0.00439$

Vertical impedance:
$k_v^* = [4GR / (1 - v)] * [(1 - \chi_v - \gamma_3 a_o^2) + ia_o(\gamma_4 + \psi_v)]$
$k_v^* = [139{,}182{,}546] * [0.500 + i(1.652)]$
$k_v^* = 69{,}591{,}273 + i(229{,}929{,}566)$

Real part = static stiffness in vertical direction = 69,591,273 lb/ft = 69,591 k/ft = 5,799 k/in

Horizontal impedance:
$k_u^* = [8GR / (2 - v)] * [1 + ia_o\alpha_1]$
$k_u^* = [98{,}774{,}710] * [1 + i(1.201)]$
$k_u^* = 98{,}774{,}710 + i(118{,}628{,}427)$

Real part = static stiffness in horizontal direction = 98,774,710 lb/ft = 98,775 k/ft = 8,231 k/in

Section 4.3 – Vibration Analysis
Foundation Stiffness (4.3.1)
$T > 2 + L_b/30$
$5 > 2 + (37 / 30)$
5 > 3.; Foundation can be considered rigid

Calculation of displacements - Vertical
Equation 4-44:
$A = (F_o / k) / [\surd ((1 - (\omega_o / \omega_n)^2)^2 + (2\beta\omega_o / \omega_n)^2)]$

- F_o = dynamic force amplitude = use Howden vertical dynamic force = 7,031 lbs
- k = vertical stiffness = 5,799 k/in
- ω_o = 93.6 rad/s
- $\omega_n = (k / m)^{0.5} = (kg / W)^{0.5} = 61.11$ rad/s
  - k = 5,799 k/in
  - $g = 32.2\ ft/s^2 * 12\ in/ft = 386.4\ in/s^2$
  - W = total system weight = concrete (545k) + machine (55.4k) = 600k
- Ignore damping; $\beta = 0$

A = 0.901 mils

Peak-to-peak motion = 2 * A = 1.802 mils

Figure 3.10 – falls within “fair” (less than 0.0785 in/s) – OK

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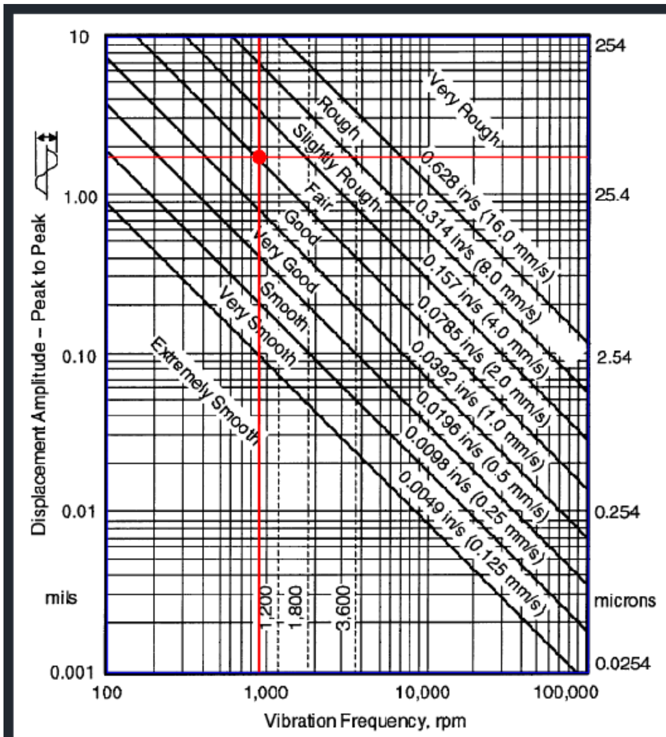

Fig. 3.10—General Machinery Vibration Severity Chart (Baxter and Bernhard 1967).

**NOTE – the term "ω_n" above (61.11 rad/s or 9.72 Hz) doesn't actually represent the natural frequency of the system because the value has been computed using a stiffness value specific to motion at a specific frequency (894 rpm or 14.9 Hz). With frequency dependent impedance, as the frequency of excitation increases, the stiffness decreases. Determining the frequency at which maximum response occurs requires an iterative solution across a range of frequencies.* *See page 53.*

Calculation of displacements - Horizontal

Equation 4-44:

$A = (F_o / k) / [\sqrt{ (1 - (\omega_o / \omega_n)^2)^2 + (2\beta\omega_o / \omega_n)^2}]$

- F_o = dynamic force amplitude = use Howden horizontal dynamic force = 7,031 lbs
- k = horizontal stiffness = 8,231 k/in
- ω_o = 93.6 rad/s
- $\omega_n = (k / m)^{0.5} = (kg / W)^{0.5}$ = 72.8 rad/s
  - o k = 8,231 k/in
  - o g = 32.2 ft/s^2 * 12 in/ft = 386.4 in/s^2
  - o W = total system weight = concrete (545k) + machine (55.4k) = 600k
- Ignore damping; $\beta = 0$

A = 1.308 mils

Peak-to-peak motion = 2 * A = 2.616 mils

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Figure 3.10 – falls within "fair" (less than 0.0785 in/s) – OK

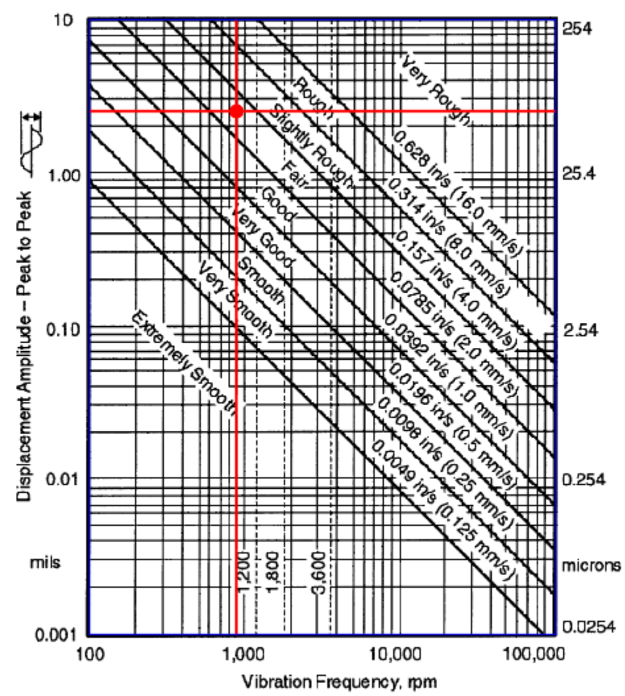

Fig. 3.10—General Machinery Vibration Severity Chart (Baxter and Bernhard 1967).