

Fig. 22 .... Vertical Forces Acting on a Vibrating Machine

The flexibility of the machine support is best expressed in terms of its deflection under the total supported static load:

$$d_s = \frac{W}{k_v} \qquad (18)$$

where

d_s = static deflection of support, inches.
W = share of weight of machine including any rigid base, resting on support, pounds.
k_v = vertical stiffness of the support, pounds per inch.

The inevitable flexibility of the machine support allows a certain amount of *vibrational motion* in response to any *disturbing forces*, such as the centrifugal force due to imbalance. This means that the machine is displaced from its equilibrium position, alternately up and down as shown in Fig. 22. Reversal at the top and bottom of each cycle requires substantial acceleration. This gives rise to an *inertia* reaction which is proportional to the mass of the machine and the square of the speed. The force balance diagrams of Fig. 23 show that the inertia force is always *opposed* to the *spring* force exerted by the supports. Thus, apart from the relatively small damping force, the *difference* between the spring force and inertia force always has to be such as to balance the disturbing force.

Since both spring force and inertia force are proportional to displacement, as shown by the formulas in Fig. 22, displacement can be calculated from Equation 18 and the condition of force balance:

$$D \times W\left[\left(\frac{RPM}{188}\right)^2 - \left(\frac{1}{d_s}\right)\right] = \frac{U}{16} \times \left(\frac{RPM}{188}\right)^2 \qquad (19)$$

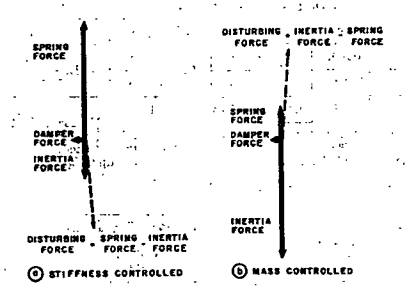


Fig. 23 .... Balance of Forces Acting on a Vibrating Machine

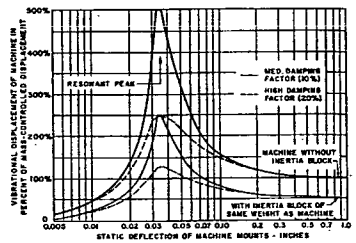


Fig. 24 .... Effect of Mount Flexibility of Support on Vibrational Displacement at 1000 RPM

where

D = displacement amplitude for negligible damping, inches.
U = unbalance, ounce-inches.

Resonance occurs when the inertia force is equal in magnitude to the spring force:

$$\left(\frac{1}{d_s}\right)_{res} = \left(\frac{RPM}{188}\right)^2 \text{ or } (d_s)_{res} = \left(\frac{188}{RPM}\right)^2 \qquad (20)$$

At resonance, the displacement of the machine is limited only by the rate at which energy is dissipated by damping in the supporting structure or machine mounts. Fig. 24 shows curves of relative displacement for a speed of 1000 rpm as a function of the static deflection for various amounts of damping and various amounts of machine weight. It should be noted that damping has a significant effect on displacement only near resonance, and that a static deflection of as little as $\frac{1}{4}$ in. will produce resonance at 1000 rpm.

When the static deflection is *much greater* than that which produces resonance, the vibrational displacement of the machine levels off and becomes independent of static deflection. Displacement for this condition can be calculated from Equation 19 by neglecting the $1/d_s$ term, and is also seen to be independent of speed:

$$D \approx \frac{U}{16W} \text{ for } d_s \geq 3\left(\frac{188}{\text{RPM}}\right)^2 \qquad (21)$$

Motion of a machine on sufficiently flexible mounts is *mass-controlled*. Displacement for a given amount of imbalance can only be reduced by adding mass to the machine, as illustrated in Fig. 24. The conditions for mass control as well as resonance are shown in Fig. 25.

When the static deflection is *much less* than that which produces resonance, the motion is *stiffness-controlled*. Displacement for a given unbalance and speed is only a function of the stiffness of the support:

$$\left.\begin{aligned} D &\approx \frac{U}{16}\left(\frac{RPM}{188}\right)^2\left(\frac{1}{k}\right) \\ &\approx \frac{U}{16}\left(\frac{RPM}{188}\right)^2\left(\frac{d_s}{W}\right) \end{aligned}\right| \text{ for } d_s \leq \frac{1}{3}\left(\frac{188}{RPM}\right)^2 \qquad (22)$$

Practical Limits for Mounting Machines Rigidly

Rigid (stiffness-controlled) mounting of a machine has some merit as the vibrational *motion* of the machine can be kept to a minimum. In practice, the condition for ridigity shown in Fig. 25 can be fulfilled only when the machine is relatively light, and the speed is relatively low.

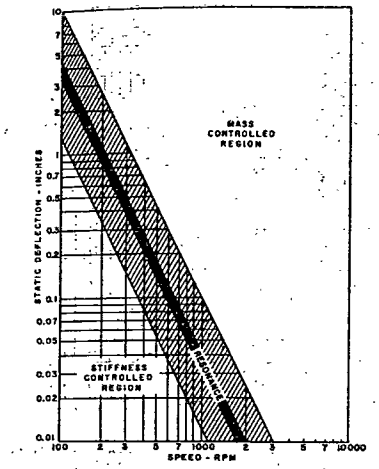


Fig. 25 .... Condition of Resonance and Approximate Regions in which Vibrational Motion is Mass-Controlled and Stiffness-Controlled

The weight of the machine has to be considered from two standpoints:

1. The heavier the machine, the more difficult it becomes to meet the condition of Fig. 25 for a rigid mounting, because of the inevitable flexibilities of the supports.
2. If a machine is installed on or suspended from a floor or roof slab, the natural frequency of the slab may be modified by more than 10 percent if the machine weight exceeds 10 percent of the effective weight of the slab. Also, the natural frequency of the machine will be affected by the dynamic properties of the structure. The two resonant speeds, which should be avoided by at least ± 50 percent, can be found from Fig. 26. The effective floor weight can be taken as the weight of that part of the slab under the projected area of the machine.

For reciprocating machinery, rigid mounting is particularly to be avoided because some of the disturbing forces at multiples of the rotational speed would fall into the resonant region.

Practical Considerations in Mounting Machines Flexibly

When a high speed machine is installed on an upper floor or other structure of low rigidity, resonance can best be avoided by mounting the machine on mounts which are sufficiently flexible to meet the condition of Equation 21. Even though large turbo-machines may appear to be rigidly mounted, the lower part of the foundation is generally designed to provide the necessary amount of flexibility.[72]

Flexible machine mounts are properly called *vibration isolators* rather than vibration eliminators or absorbers, because they confine the vibrations to the machine by allowing it to respond freely to the disturbing forces. Equation 21 may be used to estimate the *minimum* amount of displacement. Due to various simplifying assumptions made in the derivation of

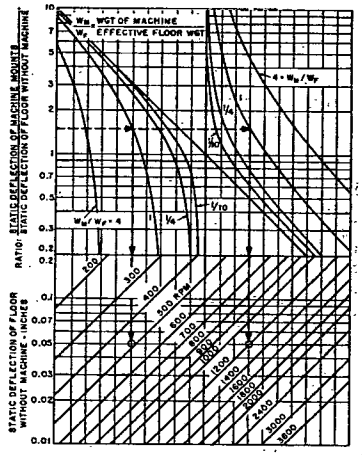


Fig. 26 .... Resonant Speeds for Machine Mounted on Flexible Floor

that equation, displacements under actual operating conditions are usually much larger and can be estimated better from Fig. 27.[75] During start up and shut down of a machine, still larger displacements will occur, at least momentarily, as the speed goes through resonance.

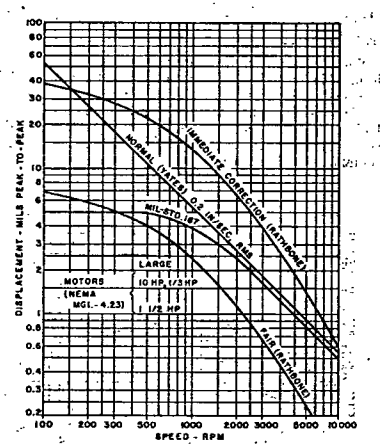


Fig. 27 .... Practical Range of Vibrational Motion for Machines Mounted on Vibration Isolators[75]