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VIBRATION EXPERT

FACTUAL DATA CONCERNING CONTRACTOR'S CHOICE OF CONCRETE VIBRATORS

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Particularly during the last decade, research has been under way concerning the chemistry and physics of concrete along with associated results to structures and roads. Publications from the Portland Cement Association and the United States Bureau of Reclamation are widely distributed and convey the present technology relative to this field and are suggested reading. The related phase of concrete placement, particularly in the area of concrete vibration, is however, only beginning to immerge from a pseudo science evolved from various sales promotions or disorganized independent works of many sincere but often times inexperienced investigators. The (organization) of knowledge will, in time, be the factor responsible for the elevation of a "jitterbug" beginning to the "science" of concrete vibration. This booklet is directed toward the (vibration) phase of the technology with a hopeful goal of providing the building contractor with a generalized conception of terms and meanings which will sooner or later be directed towards him in the form of comprehensive specification requirements. Simplified mathematics concerning the physics of rotary centrifugal vibration is included thereby offering the more serious student a base for further study. This booklet is not intended to suggest any particular model or manufacture of vibrator, but rather is directed toward providing the contractor with a more intelligent means of purposeful choice.

In spite of what we, as vibrator manufacturers, would like to be able to indicate, the concrete vibrator performs no sophisticated miracle whereby the strength of concrete is doubled or any other such wild phenomenon. THE ULTIMATE QUALITY OF CONCRETE EXISTS POTENTIALLY WITHIN ITS OWN PHYSICAL AND CHEMICAL CHARACTER AND WILL EVIDENCE ITSELF PROVIDED; THE MIXTURE RE-

MAINS HOMOGENEOUS, IS PURGED OF VOIDS (CONSOLIDATED), CONTAINS A MINIMUM OF WATER IN EXCESS OF THAT REQUIRED FOR HYDRATION, AND HYDRATES (SETS UP) SLOWLY. The primary and singular function of a concrete vibrator is to provide a peculiar transduction of energy whereby the relatively dry, viscous, unworkable plastic of a well constructed grout is temporarily transformed into a facsimilated liquid. This is possible by the complex utilization of energies in the form of motions, force and frequency.

ADVISABILITY OF "DRY MIXES"

Because a concrete mass dries and shrinks progressively from its exposed surfaces, the contracting surfaces tend to become structurally separated from the more plastic core. This process continues toward the core until the whole mass reaches its terminal moisture content and complete chemical "setting" has taken place. If the shrinkage differential is great due to rapid surface set and/or unusually high initial moisture content, the loss of strength will be severe and the resulting structure can become a type of three dimensioned jigsaw puzzle. Chloride inclusions (set accelerators) which heat the grout do not correct the fault of internal moisture differential and in themselves can weaken the bond by "sugaring" of the mud.

To achieve the ultimate inherent strength of a mix the following points are paramount in importance:

(1) The initial grout should be relatively dry in order to minimize the process of differential shrinkage during the cure. "This cannot be stated entirely in terms of a slump since some aggregates also affect the apparent slump independently of water content". Also one of the beneficial functions of air entrainment is to provide a more workable slump by the process of internal lubrication in a dry mix.

(2) The curing time should be prolonged as much as possible by surface sealing, wetting, low temperature steam, etc.; the effect being that the shrink differential can be reduced to the flexibility capacity of the particular mix.

(3) The grout must be entirely consolidated prior to any beginning of "set", internal voids must be eliminated, and no segregation of materials or densities should accompany the process.

The function of vibration lies entirely within this last (No. 3) paragraph. The advisability of relatively low initial moisture content is a prime requirement and automatically makes questionable whole groups of vibration devices which are limited to wetter or "soupier" mixes by a general lack of driving power or by some restrictive mode of application. No magic is possessed by these units whereby the damage caused by excess batching water is cancelled out. Therefore attention is directed toward vibration equipment capable of handling drier and normally lower slumps.

Dry low slump mixes by nature are viscous, and the plastic nature of these low slumps would make placement and consolidation difficult or impossible were it not for high frequency vibrators with the ability to change (at least momentarily) a near solid material into a near liquidized mass. This capacity is fundamental to the phenomenon and definition of the relationship of a liquid to a solid. A solid piece of material such as a steel block is composed of molecular parts which are in constant motion (herein called mass motion). The particles of a solid have an attractive affinity whereby the particles move together in regimented masses, in similar direction, and at more or less constant velocities. A true liquid, however, differs from a solid in that the molecular particles which compose its mass are said to have differential motion whereby the particles move independently of each other, in disorganized direction and at dissimilar velocities. This differential quality gives the material an ability to consolidate its own mass, to flow into cavities, and to purge its structure of voided spaces. This is the principle on which a vibrator works. If each grain of material can be made to move rapidly and independently of its neighbor, the mass will flow and perform the functions of a liquid no matter how stiff its unvibrated consistency. This function is not difficult to understand, i.e., if a short rapid push is given to a volume of grout the particles of the mix will be given motion; the lighter particles will begin to move instantaneously and will accelerate to high though short lived velocity in the direction of the push; heavier particles, due to greater inertia, will accelerate more slowly but will retain an assumed velocity longer. If during this period another push in a different direction is applied the lighter particles will move more nearly in the new direction while heavier grains will retain some of the forces of the initial push and move angularly to the second direction of drive. Because of the gradations of material in a mix, particle "differential" motion is achieved and in this state the grout will flow as a viscous liquid.

FREQUENCY

Experience and research have shown that a great number of differential pushes in rapid succession are required to effectively accomplish liquidization of a mix. The number of differential pushes *absorbed by the grout* during an interval is known as the number of FUNCTIONAL FREQUENCIES and is generally referred to as vibrations per minute, (VPM). The VPM given to a mass of grout by a vibrator may be greater or less than the RPM of the eccentric, but tests have shown the frequency of a well calculated design to be greater than the RPM in most cases, sometimes as high as four to eight times the RPM.

Most low slump grouts react most effectively to frequencies generated by eccentric revolutions or cycles of 7,000 to 15,000 per minute. It is not practically possible for the contractor to precisely determine the true frequency transmitted to the concrete by a vibrator although an experienced user can generally determine when the frequency is within the effective range by RPM measurement and by the *degree* of liquidation apparent in a low slump mix. Note: Special configurations or shapes of vibrator surfaces do not alter or increase the differential frequencies assumed by the concrete. "Form" or externally applied vibration even though of a high frequency rotary centrifugal origin does not instill adequate differential frequencies in low slump grouts where internal vibration to this date has been the only effective method of fluidization.

AMPLITUDE

Amplitude is the *distance* through which an impulse moves during each segment of frequency. Unlike frequency, the amplitude produced by a vibrator is not related to the rotating velocity of the machine and would remain the same quantity if the vibrator speed were halved or doubled. Amplitude of the mix is limited by a complex relationship of the vibrator's masses to the affected mass of the grout which is in opposition to the unit. Because low slump concrete is sluggish its ability to remain in contact with a rapidly pulsating vibrator is limited and if the frequency of the unit is too high or the scope of the amplitude too great, the grout will not remain in contact with the vibrator head. The unit will operate in a self-imposed void and the frequency of the mix may be considerably lower than that of the vibrator. On the other hand too small an amplitude will result in limiting the area of effectivity whereby the grout may be consolidated but will require overly close insertion spacing. There is no specific measure of amplitude which can be said to be effective in all grouts or in all cases, i.e.: Amplitude is a tensely related cofunction of frequency and within the effective range of a frequency satisfactory results are obtained if the relationship is as follows: When the frequency of vibration is near the high limit, the amplitude is to be at low limit, if the frequency is at its lower effective limit, the amplitude should be near its effective maximum. The amplitude situation is further complicated by some specific characteristics of the mix as follows:

(1) As the slump decreases, the amplitude (of the vibrator) must be increased to perform sufficient amplitude results among the particles of the mix.
(2) As the aggregate increases in size, the amplitude should be increased.
(3) Air entraining agents are used in conjunction with lower amplitudes.
(4) During periods of heavy chloride inclusion all functions of amplitude have a harmful effect upon the strength of the results.

Although the Amplitude-Frequency relationship is shown to be variable according to many conditions, the variations are directed toward a particle amplitude of from four to twenty thousandths part of an inch. "This is the amplitude of the mix and should not be confused with the no load instigation amplitude of the vibrator which is usually much greater". In spite of the highly complex nature of the function of amplitude, it is one of the easiest of all vibrator functions to determine practically by the user since serious faults are accompanied by plainly visible indicators:

(1) A vibrator with an insufficient amplitude is visibly low in grout reaction and the area of apparent effectivety will be critically small, necessitating close and frequent applications within an area of pour.
(2) Excessive amplitude, as previously stated, results in

loss of vibrator-grout contact especially when coupled with excessive frequency. This condition is manifested by the appearance of mass motion as opposed to differential particle motion (liquidization) in the grout. The vibrator seems to be violent as it "slaps" the walls of its own imposed void and although reaction will appear to be great, the quality of the finished concrete will be poor. Neither excessive or deficient amplitude has much bearing upon segregation of aggregate in dry, low slump grouts. In fact little over vibration effect is noted, in such mixes, although great ranges of vibratory functions are applied. Actually, tests show that the concrete is benefited as the vibration period is extended provided the insertion distances are well regulated so as to avoid differences in densities between adjacent lateral sections of pour.

CENTRIFUGAL FORCE

Centrifugal Force is not nearly so simple a function relative to the concrete vibrator or its effect as is generally believed and the expression of its academic quantity with regards to specifications and results is of little or misleading value. This is one of the holdovers from an unrealistic beginning of the science. I have no doubt that the term is retained because it appears impressive in print (amounting sometimes to thousands of pounds in value). (In all fairness to the equipment manufacturer it should be pointed out that the listings of centrifugal force are perpetuated by specifications which demand inclusion.) The value for centrifugal force is an arithmetical product of eccentric moment and rotational velocity and is most frequently taken from a simplified formula which assumes in effect that the vibrator barrel (the grout contacting working member) is inert, "has no motion". "Modified centrifugal force formulae are related to the performance of the machine when making calculations concerning internal bearing friction which must be overcome by additional driving torque. This is a problem for the designer and is of no consequence to the operating contractor or inspector except that the power requirements are met by the design. Centrifugal force is "related" to the important regulating aspects of vibration inasmuch as the formulae contain some of the elements of amplitude and frequency but its value does not outline the value, proportion, or character of these elements.

TORQUE:

The taxable diving torque of the rotary centrifugal vibrator is definitive of its ability to maintain a function under the load of concrete vibration. Figures or values of net available torque do mathematically describe vibrator capabilities which centrifugal force values seem to imply. Furthermore the average contractor can, without specialized equipment or unfamiliar mathematics, make surprisingly good practical comparative determinations concerning torque and the capability of a vibrator to apply the products of this torque to the mix, i.e.: Visualize that a normal internal rotary centrifugal vibrator with a balanced free running rotor in place of an eccentric element could not possibly be retarded by external pressure. In other words a balanced rotor provides no amplitude or frequency to the barrel which could act upon and be acted upon by the concrete—No work can be accomplished—No load can be translated against the driving torque. It is apparent that the capability for work exists because of the "motion" of the vibrator barrel! Conversely a unit with some form of external motion given by the complex action of an eccentric will be rotationally retarded by a force or pressure against this motion. Thus if two vibrators, one with a high output potential, and one with little output, were each clamped in a heavily loaded vise we would expect the vibrator of highest potential to be reduced in speed the greatest extent provided the driving power of the two units were equal. Similarly, if both units were disengaged from their sources of driving power simultaneously, the unit with the greatest working output will be the first to stop, providing each attains a similar initial rotational velocity. The latter method may be used if the equality of driving effort cannot be determined. The contractor can refine his practical test further by first determining the hand turned frictional resistance of the two machines in order to avoid complications occasioned by a possible internal drag of either unit. The point to stress here is, "if a vibrator is to activate a low slump mix properly, it must possess the complex capacities to translate driving torque into amplitude and frequency and it must have sufficient available torque to maintain these functions under load."

The measure of a vibrator's comparative efficiency is also based on additional factors such as handleability, durability, and ease and economy of maintenance.

Optimal vibrator performance is sometimes thought of as a mixed blessing by the contractor when many of the better functioning units seem to possess the shortest bearing lives. The eccentric suspension bearings of all effective rotary-centrifugal internal vibrators are subject to terrific overloading and this loading has additional bearing-killing characteristics in the form of high temperature and shock. The greater the effectivity of a vibrator the more pronounced are the magnitudes of these bearing destroyers. Vibrator manufacturers are often forced to reduce the effectivity of a vibrator in order to prolong the life of the bearing. However, since the business of the concrete contractor is the placement of concrete rather than the perpetuation of bearings he would do well to survey the real cost of elongated bearing life. The user will generally benefit in all areas of placement economy with a well designed vibrator whose output functions have not been sacrificed beyond an eccentric bearing life of much over 200 to 300 hours. Generally these bearings can be easily and quickly replaced and should be classed as expendable material.

In no field is an understanding of the phenomenon of centrifugal acceleration more pertinent than in the area of rotary-centrifugal vibration; and in few other applications is a reliance on "the simple academic formula" more abused or misleading.

Understanding Centrifugal Force Derivation of Formulae:

Fig. (1) Consider a mass (**m**) orbiting at constant velocity, at a constant distance (**R**) with reference to an axis at (**a**) :

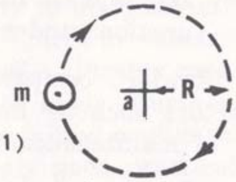


FIG. (1)

Fig. (2) Consider an instantaneous position of (**m**) at point (**A**) where the instantaneous velocity (V_0) can be given as an equivalent linear velocity in direction (**X**). During the next one quarter orbit the velocity (V_0), in direction (**X**) will be reduced until (**m**) reaches point (**B**) where the velocity in direction (**X**) will be 0. The distance traveled, in direction (**X**), during the deacceleration equals the radius (**R**).

The force (**F**) by and against the orbit = $\frac{mv^2}{2R}$ (lbs.)

(feet-pounds-seconds)

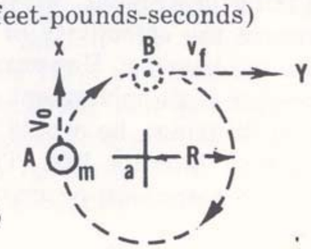


FIG. (2)

Fig. (2) NOTE that, simultaneous to the decay of velocity (V_e) in direction (**X**), mass (**m**) is uniformly accelerated toward direction (**Y**). The velocity (V_f) begins at point (**A**) with an 0 value and reaches its maximum linear equivalent relative to direction (**Y**) at point (**B**). The distance traveled in direction (**Y**) during the acceleration is equal to the radius (**R**). The force by and against the orbit fixing tension: $F = \frac{mv^2}{2R}$. Because the acceleration and deacceleration are coacting functions and because their values are numerically equal, the total force becomes: $F = \frac{mv^2}{R}$. Conversion of terms to weight (pounds)-rpm-radius (inches), the formula becomes:

Centrifugal Force (pounds) $F = .000028416\ wRrpm^2$
(simple academic formula)

This formula satisfies the general arithmetic of centrifugal force, but, as indicated by general misconceptions, apparently offers little insight into the physics involved here. The formulation seems to indicate to some that the position of the axis of the orbit exists within an infinite mass of some undefined anchor body. Possibly this is the *whole* problem, "where to put the axis". In the case of a rotary centrifugal vibrator, this axis must be defined as giving vibratory motion to the anchor mass or barrel of the unit.

Dynamic Equilibrium:

Two bodies in cooperative orbit, when held by a force resisting link or environment, tend to rotate around their aggregate center of mass; and the forces generated against this center by one are equal in magnitude and opposite in direction to those generated by the other.

Fig. (3) Consider the elements of a rotary centrifugal vibrator with: (w#) The effective eccentric weight.

(W#) The inert load of the barrel, bearings, etc., with the inert axis of rotation at the (W) center of mass.

(R″) The fixed distance between the centers of mass of (w) and (W).

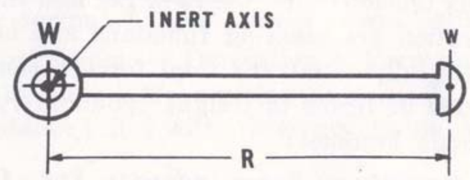


Fig. (4) Location of the Kinetic Axis:

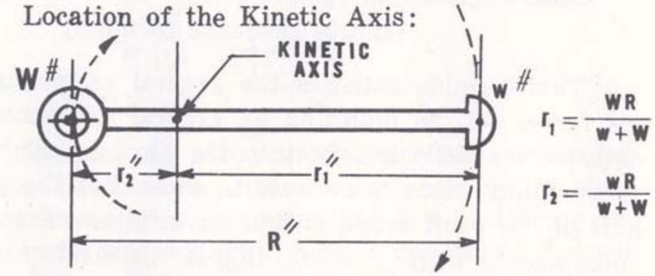
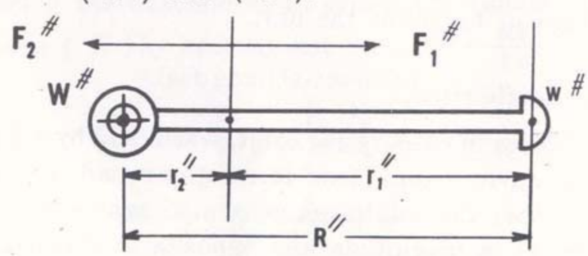


Fig. (5) No load Centrifugal Force — Tension between (W) and (w).



$$F_2 = .0000284 W r_2 rpm^2 = F_1 = .0000284 w r_1 rpm^2$$

$$= .0000284 \frac{wWR}{w+W} rpm^2$$

Fig. (5) Forces (F_1) and (F_2) are in opposing equilibrium and represent a tension within the system whereby each is the restraint of the other. These forces may exist as linkage stress or bearing pressure but *they do not define an ability to do external work.*

Fig. (6) The system has a capacity to perform external work by virtue of the amplitude and frequency of (**W**) (the contacting medium), *provided sufficient torque or driving power is available to sustain the functions.*

Suppose a mass of weight (L_0#) is contacted by (**W**#) in such a way as to offer resistance to the motion of (**W**) : Some of the energies of the centrifugal system will be transformed into energy given to (L_0) .

The shift of the kinetic axis of the system;

$$r_a'' = \frac{wR''}{w+W} - \frac{wR''}{w+W+L_0}$$

The maximum amplitude given to (L_0) and shared by (**W**) ;

$$r_2'' = \frac{wR}{w+W+L_0}$$

** The resulting force directed toward (L_0) by the vibrator;

$$F\# = .0000284\,(w+W)\,r_a\,rpm^2$$

The maximum retaliation pressure of (L_0) against the vibrator;

$$\underline{P}\# = \underline{.0000284}\,\underline{L_0}\,r_2\,rpm^2$$

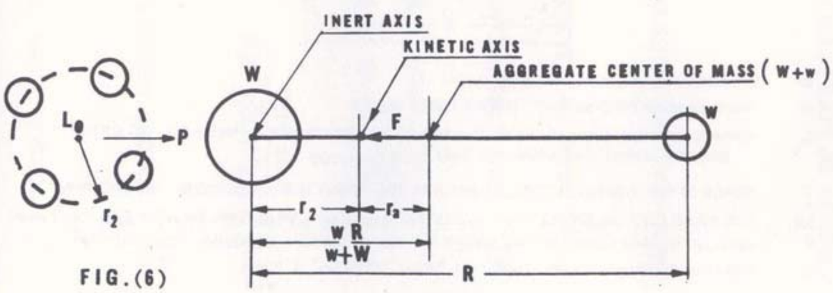
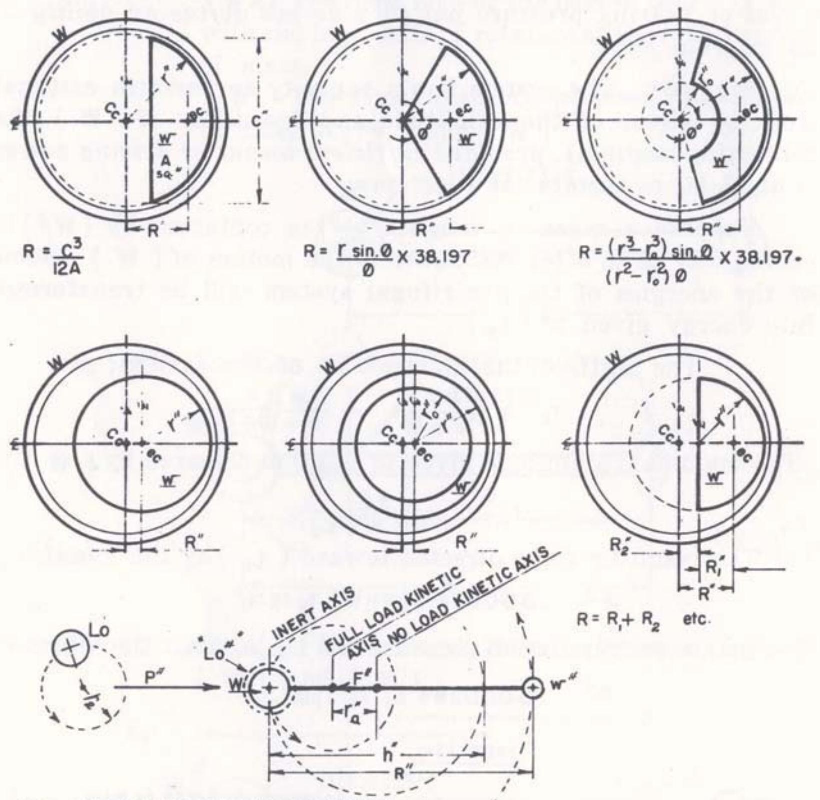


FIG. (6)

CENTERS OF MASS OF SEVERAL COMMON ECCENTRICS (ec)

INERT AXIS OF ROTATION AT THE C/M OF THE INERT LOAD(W) (Cc)

R — THE DISTANCE BETWEEN Cc and ec (INCHES)



w'	EFFECTIVE ECCENTRIC WEIGHT (LBS.)
W	RIGID CONCENTRIC WEIGHT (INERT LOAD) (LBS.)
r_a	NOMINAL ORBITAL DISPLACEMENT CAUSED BY THE RETALIATIVE PRESSURE (P) OF THE GROUT AGAINST THE VIBRATOR (IN.) = $\frac{wR}{w+W} - .005$
F	FORCE OF THE VIBRATOR APPLIED AGAINST THE GROUT (LBS.) = $.0000284\ (w+W)\, r_a\, RPM^2$
Lo	THE MASS EQUIVALENT OF P → AT THE RESONENT NULL OF NORMAL GROUT = $200\,wR - (w+W)$
P	RETALIATIVE PRESSURE BY THE GROUT AGAINST F (LBS.) = $.0000284\ (.005\,Lo)\ RPM^2$
h	FUNCTIONAL NO LOAD AMPLITUDE (IN.) "PEAK TO PEAK" = $\frac{2w'R}{w+W}$ "½"

T_1 TORQUE GIVEN TO BALL BEARING FRICTION (LB. IN.) "U"

$$= .0000284 \ RPM^2 \left(\frac{wWR}{w+W} - Wr_a \right) .006 (\text{P.R. OF BEARING"})$$

T_2 TORQUE REQUIRED TO SUPPLY THE ENERGY TO THE WORK (LB. IN.)

$$= .0000142 \ (w+W) \ r_a^2 \ RPM^2$$

H.P. $= \dfrac{(T_1 + T_2) \times RPM}{63,000}$

V. NET VOLUME OF EFFECT AT T = $^{*}\dfrac{Lo}{1330} \sqrt[3]{\text{SLUMP"}}$ (CU.YD.) NOTE: 1330 = LBS./CU.YD. X.35

* "VALID FROM 1/4" TO 4" SLUMP"

T NOM. TIME REQUIRED TO CONSOLIDATE V $= \dfrac{105,000}{RPM}$ (SEC.)

TRUE CAPACITY (CU YDS/MIN.) $= ^{*}\dfrac{Lo. \ RPM \sqrt[3]{\text{SLUMP"}}}{2,329,000}$

NOM. HAND OPERATED CAPACITY (INC. 6 SEC./REQ. MOVEMENT)

$$\text{CU. YDS./HR.} = ^{*}\frac{Lo \sqrt[3]{\text{SLUMP"}}}{2.218 \left(\frac{17,500}{RPM} + 1 \right)}$$

RADIUS OF EFFECT (IN.) $= 122 \sqrt{\dfrac{V}{\text{ACT. DEPTH"}}} = 1.066 \sqrt{Lo \sqrt[3]{\text{SLUMP"}}}$ (AT NOM. 10" WORKING LENGTH)