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Dynamic Response Studies of Machine Tools Foundation: Critical Analytic Models Versus ANN

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Abstract
Machine tool dynamic response studies are interesting research areas and will continue to attract attention among researchers in this field. This is born out of the fact of the effect and consequences of vibration of the machine tool foundations. Vibration unless designed for, is detrimental to machine tool performance and is important for it to be reduced or eliminated. Proper machine tool foundation is required to absorb and transmit the vibratory forces due to unbalanced masses and misalignment to the soil. Many analytic models have been developed and applied with various degrees of limitations and therefore begging for further researches. This paper is focused on highlighting prominent works in this area and show casing the promises that Artificial Neural Network can proffer in dynamic response studies of machine tool foundations.
Keywords: ANN, dynamic, foundation , machine tool, models, vibration, response
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I. Introduction

Machine tools are one of the major components that drive both industrialization and productivity advancements in every modern society, they have witnessed continuous evolution from hand held simple devices into heavy duty machineries that could handle higher and more complex forms of production. In order to perform at a satisfactory level, a machine tool must be rigid to both static loads and dynamic loads as well. Its static stiffness determines its ability to produce components with a high degree of dimensional accuracy while its dynamic stiffness impacts on factors such its surface finishes and maximum chip removal rates that can be achieved [1]. Over the years as studies try to enhance operating life of these machine tools and also improve upon the precision, vibrations have been identified as one of the key areas to which a lot of attention has to be paid.

A good design of the machine tool foundation has been noted to go a long way in limiting these vibrations. The main aim in the design of a machine foundation is to a considerable extent limit its relative motion to amplitudes which will be satisfactory or in other words would not endanger the operation of the machine nor will the people and machineries working in the immediate surrounding be disturbed. Therefore, a key consideration to a successful machine foundation design is the careful engineering analysis of the foundation response to the dynamic loads from the anticipated operation of the machine [2]. A machine tool foundation in addition to its primary function of providing a rigid bed for supporting the static loads arising both from self -weight and the mass of the machine also to a considerable extent acts as an absorbent for the dynamic forces arising from the operating of the machines.

In the past, simpler methods were utilized for the design of foundations, these methods most often involved the multiplication of static loads by an estimated dynamic factor and the result being treated as an increased static load without any knowledge of the actual safety factor. Because of this uncertainty, the value of the adopted dynamic factor was usually too high, although practice showed that during operation harmful deformations did result in spite of using such excessive factors [3]. This prompted extensive researches in the field of the dynamic response of machine tool foundations.

Dynamic response studies of machine tool foundation could be defined to be the analysis of the manner in which foundations responds to motion arising from both static and essentially dynamic forces. Most foundation of large machines are subjected to vibrations, these vibrations are as a result of disturbances which differ in form and origin, the disturbances could be propagated to the foundation through the soil from surrounding sources or could be as a result of forces or moments from the machine that it bears, these disturbances excite the machine foundation system and set it into motion[4]. If these excitements resulting are not properly managed by the foundation, either by rigidity or by transferring to the underlying soil, it could lead to a whole lot of problems which includes noticeable reduction in dimensional accuracy while operating the machines, reduction in operating tool life of machine tools and in extreme cases failure of the foundation itself. The amplitude of vibration and operating frequency of a machine are the most important parameters to be considered in analysis of machine foundation. One of the key factors in the dynamic analysis of a foundation system is to estimate the resonant frequency and amplitude under machine loading, and in turn estimate impendence functions of an associated rigid foundation **[**5].

Not paying necessary attention to the design of foundations could prove to be catastrophically as it leads to economic losses, breakdown in production cycles, uncomfortable working environments, and outright physical hazards. Therefore special attention needs to be paid in their analysis and design.

Manufacturing companies spend a considerable amount of resources in the purchase of machineries and also on the installations, hence detailed attention needs to be paid to the area of machine foundations as previous research has proven that properly designed foundations play a vital role in maintaining a better machine tool life, so in order to prevent these expenses from becoming a burden via recurring budgets findings from this research needs to be utilized.

Machine tool foundations could simply be viewed as the rigid support upon which machine tools rest or are installed. Due to the nature of operation of most of these machineries, the supporting structure has to possess some vital characteristics in order to ensure smooth operations. In earlier times, the foundation was just viewed as a support for the static loads which are basically the weight of the machine it carries, but with this overlook came various complications, hence the need to take into account the dynamic loads acting upon these foundations [6].

In earlier years, simpler but inefficient methods of calculation were used, these methods usually often involved the multiplication of static loads by an estimated dynamic factor and the result being treated as an increased static load without any knowledge of the actual safety factor. The major flaw associated with this system of analysis was that the value usually arrived from it as a dynamic factor was usually too high leading to higher costs in the design and production of corresponding foundations, yet studies showed that during operation undesirable deformations occurred, hence the need for deeper investigation. Based on studies over the years, it has been found out that it is insufficient to base the design of foundations on only the vertical forces as there are also other forces acting on the foundation in various axis**.** Further stipulated that the criteria for foundation selection does not only depend vertical forces that it supports, but also the manner which it handles the dynamic loads it is exposed and these depends on the speed of the machinery, operating amplitudes and the natural frequency of the foundation.

Through years of comprehensive research by various scientists and engineers utilizing various mathematical and experimental tools, standards have been arrived for the maximum safe vibration amplitude of machine tool foundation systems and also allowable deformation

1.2 Types of machine tool foundations

Foundations for machine tools could be classified into various types, one of the major criteria for these classification is based on the structural geometry, and under these we have [7].

(i) Block type foundations: as the name implies, these are usually in the shape of cuboids. They are mainly a cast of reinforced cement concrete, equipped with holes for bolts and other accessories depending on the type of machine tool it would be utilized for. These type of foundations are the most widely used due to their relatively less complex geometry and also because dynamic machines are preferably located close to ground level in order to reduce the elevation difference between the machine dynamic forces and the centre of gravity of the machine tool foundation system. The dynamic response of such foundations generally depends on analyzing the block as a rigid structure.

(ii) Table top foundations: these type of foundations usually consist of an elevated slab supported concrete columns. It is utilized for turbine machineries and other machineries which have accessories such as pipes which could be fitted below the table top. The dynamic response of these type of found is more complex as it depends on the motion of its different components. The table top could sometimes be fitted with vibration isolators to further enhance their effectiveness.

(iii) Pile foundations: these type of foundations is mostly utilized where the soil has been found to have low carrying capacity therefore resulting in low allowable contact pressures. Piles are special structures which are capable of transferring axial loads into the underlying soil by utilizing components such as end bearings and frictional side adhesion. The piles are designed in such a way that transverse loads are withstood against the side of the pile. One of the main aims of the pile foundation is to avoid over transmissibility to supporting soil and also to prevent resonance in the system [8].

(iv) Box or cassion type foundation: these type of foundations is quite similar to the block type, the major difference being that unlike the block foundation, the box type consists of a concrete block but with a hollow centre. This hollow centre results in a reduced mass than that of equal dimensions with the block foundation and consequently an increased natural frequency.

(v) Wall foundations: wall foundations consists of a pair of walls supporting a top slab, the machine rests on the top slab. Foundations found under this category are quite similar in structure to the table top foundations, it is economical for smaller projects. Wall type machine foundations in their design should be made from homogeneous material in case of both horizontal and vertical member.

The common machine foundations are shown in Figures: 1a and 1b and Figures 2a and 2b respectively;

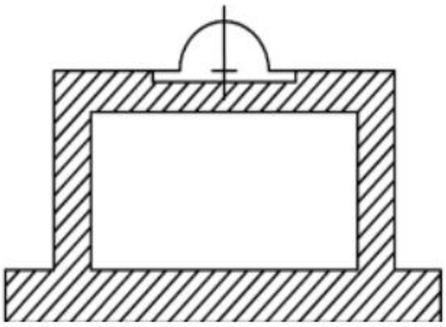

Figure. 1a : Box Type machine foundation [7]

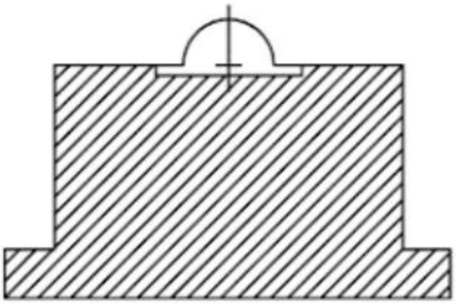

Figure 1b : Block Type machine[7] foundation

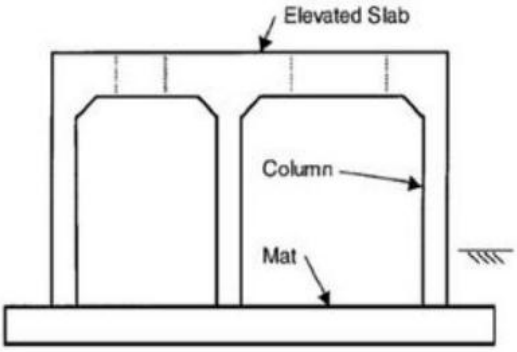

Figure 2a: Table-top machine foundation[9.7]

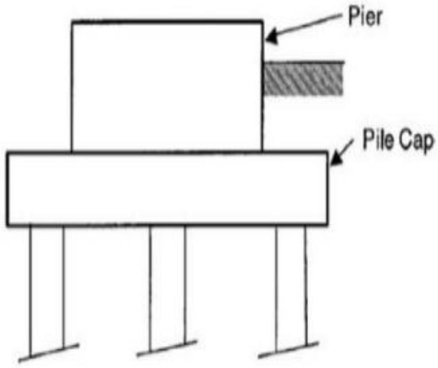

Figure2b: Pile type machine foundation[9]

1.3 General design criteria for machine tool foundations

It has already been established that the performance of machine tools rely heavily on the foundations upon which they rest. For this to be the case, the following requirements should at least be satisfied [9]:

(i) The foundation should be rigid enough to bear the machine without crushing or failure.
(ii) It should not be prone to excessive settlement, this should be kept within allowable limits.
(iii) There should be no resonance during operation, in essence the natural frequency of the foundation system should not coincide with the operating frequency of the machine.
(iv) The amplitudes during operating condition should be within allowable limits. These limits are usually specified by the machine manufacturer.

Figure 3 shows the various vibration ranges and their effects to the immediate surroundings.

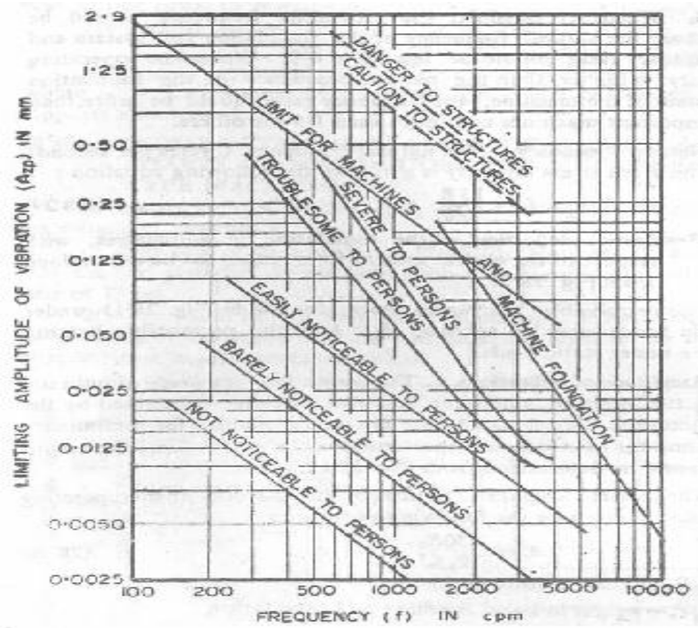

Figure 3: Various vibration ranges and their effects[10].

1.4 Earlier methods of dynamic analysis

With the surge in production and the utilization of machine tools as the driving force of the industrialization came the need to look into ways to make the operations smooth and accurate as well as also to try and ensure that an acceptable tool life durability is achieved to avoid re occurring cost showed vibrations to be one of the main stumbling blocks, hence the need for studies in ways of mitigating this problem.

The empirical methods formed the bedrock upon which many of the advancements in this area was built on. One of the early notable approaches to this cause was carried out by the German society for soil mechanics (DEGEBO) in the early 1930s, mechanical oscillators were used to excite the underlying soil in a bid to ascertain the dynamic properties of soils[11] . Following the DEGEBO experiments and improving upon lambs work on half space theory. [12] came up with a theoretical means of evaluating the dynamic response of vibrating footings as influenced by soil properties, as at the time of its proposal, Reissner's theory was heavily criticized due to the fact that results obtained from its analysis usually differed from field obtained results by a wide margin, this problem was traced to some factors which included the assumption of a uniform contact pressure, elastic soil medium, and geometry of contact area [13] even though [12] study had its flaws, it formed the basis upon which many other researches were built upon.

1.5 In phase mass

[14] came up with a concept which assumed that a given mass of soil directly the footing moves rigidly and in-phase with foundation[2]. The main aim of the concept was to determine the resonant frequency of the foundation system while neglecting the damping effect. The in phase mass method was far from what was obtainable realistically due to the fact that unlike the assumption made, the soil does move as a rigid body with the foundation footing, but rather exhibit a shear and oscillatory movement as waves are propagated at the footing-soil interface[2], there was also extremely difficulty in evaluating the exact mass in phase with the foundation footing, as this depends on a lot of factors such as the dead load (total of the mass of the machine and foundation), mode of vibration, type of force exciting the system, contact area as well as the properties of the soil [15]. The equation for the in phase mass was given in Equation 1.

$$F_n=\frac{1}{2\pi}\sqrt{\frac{K_V}{M+M_S}} \qquad \text{Equation 1}$$

where
M is the total dead load resting on the soil (mass of the foundation and machine).
M_S is the mass of vibrating soil (in phase mass).
F_n is the Natural frequency.
k_v is the spring constant.
The in phase mass being one of the very early methods of dynamic response served its purpose as at the time but

also had a major flaw which was that although it was based on the mass of the soil acting in phase with the foundation, it failed to take into consideration the effects the different soil properties would have on the system.

1.6 Reduced natural frequency method

[15] improved on the in-phase mass method by going a step further to consider the types of soil and the effects on the system. This concept suggested that the natural frequency of the foundation-soil system was solely a function of the soil bearing pressure capacity, the contact area and also the different types of soil [16]. The method was known as the reduced natural frequency method due to the fact that as the soil was put into consideration, the natural frequency of the system was reduced. The Equation for the in-phase mass can be as shown in Equation 2.

$$F_n = \frac{1}{2\pi}\sqrt{\frac{K'_V\ A}{M+M_S}} \qquad \text{Equation 2}$$

where:
M is the total dead load resting on the soil.
M_S is the mass of vibrating soil(in phase mass).
F_n is the Natural frequency.
K'_V is dynamic modulus of subgrade.
A is the cross-sectional area of the foundation footing.[15]further considered the static pressure exerted by the foundation footings on the underlying soil, hence the Equation 2 is modified and presented in Equation 3.

$$F_n = \frac{1}{2\,\pi}\sqrt{\frac{A}{F}}\ F_{nr} = \frac{F_{nr}}{\sqrt{q_o}} \qquad \text{Equation 3}$$

where F_{nr} is the reduced natural frequency and is obtained as shown in Equation 4.

$$F_{nr} = \sqrt{\frac{K'_V\ g}{1+\frac{M_S}{M}}} \qquad \text{Equation 4}$$

where:
q_o is the vertical pressure between foundation footing and the soil, obtained by; $\frac{F}{A}$. The applied force per unit area.
g is the acceleration due to gravity.
F is the force exerted by the footing and machine on the soil.
The reduced natural frequency was used for design procedures following a procedure of first obtaining the natural frequency, then using the total weight of the footing, the static bearing pressure is calculated. The next step is to use Equation 4 to calculate the reduced natural frequency and cross reference it with the**[**15] chart to obtain a required area for a no-resonant criteria, this required area should be less than the estimated area . The main flaw of this approach was that it was mainly concerned with resonant frequency while not taking into account the vibration amplitudes, also it was most times interpreted to mean that the soil bearing pressure was the most important factor in foundation design [17]. Figure 3 shows a plot of the reduced natural frequency chart.

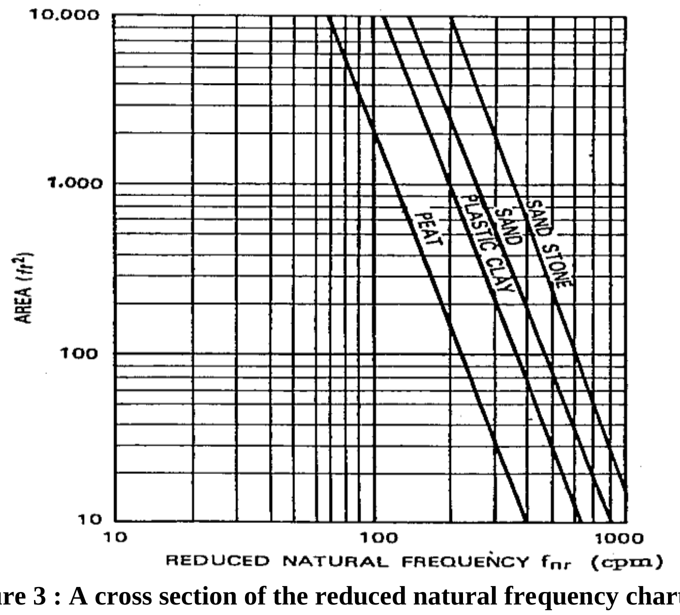

Figure 3 : A cross section of the reduced natural frequency chart[15].

1.7 Wrinkler Method

In the 18th century, Wrinkler proposed a method for the analysis of foundations which employed the linearising of the soil behavior. The wrinkler model also known as the "elastic subgrade reaction" hypothesis attempts to represent the soil behaviour under loading in the simplest means, it tried to achieve this by representing the soil medium by independent vertical springs which signifies the soil stiffness resting on rigid plates. This model was one of the most notable early approaches that utilized the mass-spring dashpot approach, and one of its major characteristic was that the contact pressure between the foundation and underlying soil is directly proportional to the accompanying vertical displacement of the soil medium [18].

As the model was further scrutinized, a defect was noted in the sense that it could not sustain shear stresses, and also could not spread loads to surrounding parts which were not directly loaded **.**

[19] model does not include dampers in the system. In a bid to check these defects a dynamic [19] model was put forward which included viscous dampers added parallel to the independent springs, this model was known as wrinkler-voigt model in a bid to give credit to Voigt who adopted the use of the viscous dampers.

Further improvements to the [20] model was done by [19] after he conducted series of place bearing tests and put forward an experimental based chart of the coefficient of subgrade reaction (spring constants) of various soil types and under various modes of vibration**.[**19] also showed that the dynamic coefficient of subgrade reaction is approximately equal to the ratio of applied pressure to the resulting displacement when repeated static load tests were performed.

For an undamped system subjected to vertical harmonic oscillation, the equation of motion is given by Equation 5:

$$M\ddot{U}_V + k_v U_v = P_O \sin(wt) \qquad \text{Equation 5}$$

where:

M is the lumped mass of the foundation and the machine (oscillating body).

w is the forcing frequency.

$k_v$is the vertical spring constant.

U_v is the vertical displacement.

P_O is the force amplitude.

t is time.

The vertical displacement U_v is given by Equation 6:

$$U_v = Asin(w_o t) + Bcos(w_o t) + \frac{\frac{P_O}{k_v}}{1-\frac{w^2}{w_o^2}} (\sin(wt) \qquad \text{Equation 6}$$

where:

w_o is the natural frequency of the system and is given by $\sqrt{\frac{k_v}{M}}$

A and B are constants.

For a steady state condition, the displacement amplitude obtained and presented in Equation 7:

$$U_v = \frac{(^{P_o}/_{k_v})}{(1-\frac{w^2}{w_o^2})}. \qquad \text{Equation 7}$$

The model however provided no information on its spring and dashpot coefficients, rather these were obtained from dynamic plate tests conducted in the field. In other to achieve this, the field obtained amplitude and frequency at resonance were utilized in calculating these coefficients. Field results observed differences between the spring constants obtained from the plate tests and those from static repeated loading and hence suggested that the "in-phase mass" concept as a means of matching results from both types of field testing. A free body diagram of [20] model is shown in Figure 4.

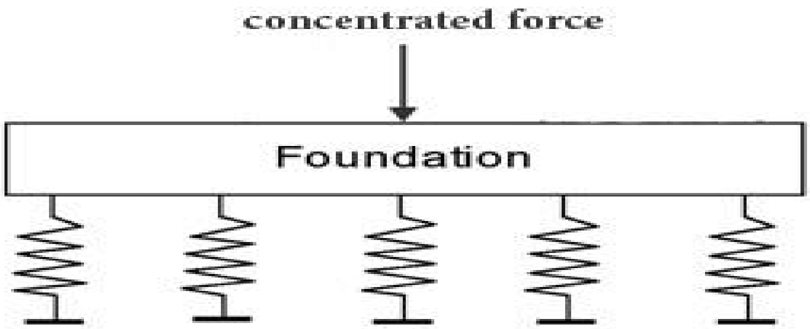

Figure 4: Wrinklers model with concentrated loading[20].

Although the [20] model was widely accepted and utilized, there could be seen some notable limitations in this model such as the fact that the model tends to work on the assumption of the existence of a linear stress-strain behavior of the underlying soil which is not what happens in actual scenarios.
Also the springs utilized in the model are represented in a way that they are considered independent of one another and hence there is no interaction between them, this would mean that the deformation of the underlying soil would only be in directly in only the loaded area, this assumption is not realistic since the soil is a continuous material.

1.8 Filanenko Borodich model

This is a notable further contribution to wrinkler's model, here it required a means of continuity between the various individual soil spring elements represented in the wrinkler's model, it adapted the assumption of a stretched thin elastic membrane with a constant tension as the means of continuity [21]. The introduction of this continuity parameter made it better at considering the behavior of soil at both sides of the foundation footing. The tension is responsible for maintaining the continuity even when undergoing deformations.
The governing equation of the model is given by Equation 8.

$P = kw - T\nabla^2 w$ Equation 8

where:
P is the pressure on the soil.
k is the coefficient of subgrade reaction.
w is the deflection.
T is the tension of the elastic membrane.
∇^2 is a laplace operator.
[21]model can be represented schematically as shown in Figure 5.

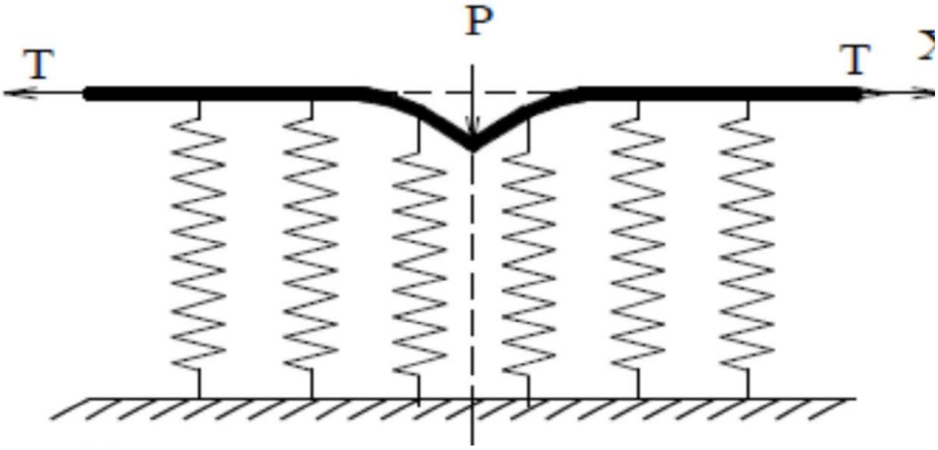

Figure 5 Filanenko Borodich model with concentrated loading[21].

1.9 Elastic half-space theory

The elastic half-space theory was formed as an improvement to the findings to Lambs solution in 1904 while attempting to solve the problem of an elastic semi-infinite solid caused by a concentrated load. [12] conducted the first engineering application of this principle while carrying out studies on the response of a vertically loaded cylindrical disc on an elastic half space.
[12] proceeded with the assumption that the soil carrying the foundation is a semi-infinite homogenous, isotropic body undergoing a vertical, uniformly distributed symmetrical surface pressure[13] , in addition, the soil properties required to body were the poisson's raio, shear modulus of the soil as well as the mass density[22]. [12]'s study also showed the existence of radiation damping, a phenomenon which until his finding was not clearly understood and taken into consideration. Radiation damping could be defined as an occurrence in which whenever a foundation footing moves against the underlying soil, stress waves are developed at the contact surface and are carried outwards in the form of body and surface waves [2].
[14] proposed that the vertical displacement at the centre of a uniformly loaded circular footing could be obtained as given in Equation 9.

$U_v(t) = \frac{P_o e^{iwt}}{G r_o}(f_1 + i f_2)$ Equation 9

where:
U_V is the vertical displacement.
t is time
P_O is the amplitude of the Dynamic load.

G is the shear modulus.
r_o is the radius of the footing.
w is the frequency of excitation.
i is a complex number $\sqrt{-1}$.
f_1 and f_2 are known as frequency dependent functions, and they show the influence of poisson's ratio as well as the shear wave velocity.
[14] further suggested a_o (a dimensionless frequency) which was given by Equation 10:

$$a_o = wr_o\sqrt{\frac{\rho}{G}} = \frac{wr_o}{V_s}$$ Equation 10

where :
ρ is the mass density of the soil.
V_s is the velocity of shear wave propagated.
In order to express his model using a mass-spring dashpot model, [12] introduced a dimensionless term which he called the "mass ratio" and it is given by Equation 11.

$$b_o = \frac{m}{\rho r_o^3}.$$ Equation 11

where:
m is the mass of the system.
ρ is the mass density of the soil.
r_o is the radius of the footing.
Using a mass-spring dashpot model,[12] Equation is presented in Equation 12.

$$U_v = \frac{P_o}{Gr_o}\sqrt{\frac{f_1^2+f_2^2}{\left(1+b_o a_o^2 f_1^2\right)^2+\left(b_o a_o^2 f_2^2\right)^2}}$$ Equation 12

The phase angle between the external force and the ground displacement is represented by ϕ and expressed as given in Equation 13:

$$tan\phi = \frac{f_2}{f_1+b_o a_o^2(f_1^2+f_2^2)}$$ Equation 13

The phase angle between the external force and the footing displacement is represented by φ and also expressed as in Equation 14:

$$tan\varphi = \frac{f_1}{f_2}$$ Equation 14

In addition to the unrealistic assumptions made by [12] of uniform contact pressure, elastic soil medium, and geometry of contact area[13] also exposed that an algebraic error of sign used in calculation of the displacement function f_2 was a reason the discrepancies noticed when the results from [12]study were compared with those obtained from the field.
Further improvement to [12] study was done by Bycroft in 1956 in an attempt to evaluate the effect of the distribution of pressure at the point of contact between the foundation and the half-space.

1.10 Lysmer's Model

[23] further analysed the theoretical situation presented by [12]. He obtained the solution for the vertical axis symmetric vibration by approximating the contact surface into concentric rings of uniform frequency dependent stresses acting in the vertical axis with consistent boundary conditions [2]. [23]suggested that the behavior of a vertically loaded foundation can be fundamentally be shown with a single degree of freedom 'mass-spring-dashpot' model with frequency dependent stiffness. As an improvement to [12]s approach, which relied on estimates of the displacement functions (f_1 and f_2) obtained from charts, [23] instead multiplied the term (f_1 + if_2) from[12]'s equation for calculating the vertical displacement by 4/(1-v), this reduced the influence of the poisson's ratio, this is shown by Equation 15:

$$F = \frac{4}{(1-v)}(f_1 + if_2) = F_1 + iF_2$$ Equation 15

The new functions F_1 and F_2 could be calculated independently by the Equations 16 and 17 respectively:

$$F_1 = \frac{-f_1}{f_1^2+f_2^2}$$ Equation 16

$$F_2 = \frac{f_2}{f_1^2+f_2^2}.(1/a_o)$$ Equation 17

[23]Lysmer went ahead to show the influence of the geometry of a vertically vibrating circular footing by introducing a modified mass parameter shown in Equation 18:

$B_v = \left(\frac{1-v}{4}\right)\frac{m}{pr_0^3}$ Equation 18

where v is the poisson's ratio.

Hence unlike in[12]'s study, the[23] model does not require a chart to extract the values of f_1 and f_1 since it can readily be calculated by specifying the geometry of the footing in question, the frequency of the exciting force and the nature of the soil**[**24].

The equation of motion for the**[**12]'s model is expressed as shown in Equation 19:

$M\ddot{U} + C\grave{U} + KU = P_O \sin(wt)$ Equation 19

where:

M is the total mass of the system.

C is the viscous damping coefficient of the system.

K is the stiffness of the system.

P_o is the force amplitude.

U is the displacement of the system.

w is the forcing frequency.

t is the time.

The amplitude of the vertical displacement is given by Equation 20 :

$U_v = \frac{(1-v)P_o}{4Gr_o}Z$ Equation 20

Z in the equation is the magnification factor.

Considering vertical vibration, the viscous damping coefficient (C) is represented with C_v and is obtained by Equation 21.

$C_v = \frac{3.4r_o^2}{1-v}\sqrt{\rho G}$ Equation 21

Also, in the same manner, the vertical stiffness K_v is given by Equation 2.22:

$K_v = \frac{4Gr_o}{1-v}$ Equation 22

where:

r_o is the radius of the footing.

G is the shear modulus of the soil.

v is the poisson's ratio of the soil.

ρ is the density of the soil.

The quantity D is given by Equation 23:

$D = \frac{C_V}{C_C} = \frac{0.425}{\sqrt{B_V}}$ Equation 23

where C_c is the critical damping coefficient of the system is shown in Equation 24:

$C_C = 2\sqrt{K_V M}$ Equation 24

1.11 Veletsos and Verbic model

[25] proposed a model which later came to be known as the massless soil model. Prior to this, previous methods tend to adopt the assumption that the footing and soil are massless while trying to determine the dynamic response of machine foundation systems following tests which usually utilized forced vibrations [23]. Further studies showed that the more realistic means of analyzing the dynamic response of foundation systems could be by adopting the assumption that the footing is rested upon a column of soil with its mass distributed across its width and length [25], when this column of soil is subjected to a vertical harmonic load, it vibrates with the mass of soil spread across its length and width. For analysis at low frequency (a_o ,which is [12]'s dimensionless frequency is less than or equal to 1.5) however the column could be assumed to be massless and the distributed mass lumped and placed upon a spring and dashpot.

The dynamic stiffness of the system can be obtained by Equation 25.

$K(w) = K_o(k(w)(a_o v) + ia_o c(w)(a_o v))$ Equation 25

where:

a_o is the dimensionless frequency.

v is the poisson's ratio.

K_o is the the static stiffness.

$k(w)$ is the dynamic stiffness coefficient.

c(w) is the damping coefficient.

[25] through further analysis produced a table through which the dynamic stiffness coefficient (kw) and the damping coefficient could be obtained from Equations 26 and 27.

Using the coefficients from the table:

$$k(w) = 1 - b_1 \frac{(b_2 a_o)^2}{1+(b_2 a_o)^2} - b_3 a_o^2 \quad \text{Equation 26}$$

$$c(w) = b_4 + b_1 b_2 \frac{(b_2 a_o)^2}{1+(b_2 a_o)^2} \quad \text{Equation 27}$$

However for analysis at higher frequencies, the lumped mass is represented by M_s and is shown by Equation 28:

$$M_s = (1 - k(w)) \frac{K_o}{w^2} \quad \text{Equation 28}$$

Substituting the frequency w^2 with the dimensionless frequency a_o and [23]'s mass dimensionless parameter B_v, then M_s is given by Equation 29.

$$M_s = B_v \frac{K_o r_o^2}{V_s^2} \quad \text{Equation 29}$$

where V_s is a parameter obtained from elastic theory and is given by Equation 30

$$V_s = \sqrt{G_o/\rho} \quad \text{Equation 30}$$

G_o is the shear modulus of the soil.
ρ is the density of the soil.
The natural frequency of the system is given by Equation 31:

$$w_n = \left(\sqrt{\frac{K_o}{M_s + M_f}}\right) \times w_o \quad \text{Equation 31}$$

where:
w_n is the natural frequency of the system.
M_f is the inertia of the footing.
W_o is the natural frequency of the system assuming the half space is massless.
The displacement amplitude of the foundation system is given by Equation 32:

$$U_v = \frac{\frac{P_o}{K_o}}{\sqrt{\left(1-\left(\frac{w}{w_n}\right)^2\right)^2 + 4D^2\left(\frac{w}{w_n}\right)^2}} \quad \text{Equation 32}$$

where D is the damping ratio of the system and is obtained by Equation 33:

$$D = \frac{C}{2\sqrt{K_o(M_s + M_f)}} \quad \text{Equation 33}$$

1.12 Impedance Functions

Impedance functions are a very important factor in the dynamic analysis of foundation systems. They generally refer to the frequency dependent stiffness and damping of the interaction between the foundation footing and the soil it rests upon. These functions describe an assumed linear relationship between the force and displacement at a particular frequency of a dynamically loaded machine foundation**.** It could also be defined as the ratio between the steady state force and the resulting displacement at the base of the foundation at a particular frequency of excitement [2] and is shown in Equation 34.

$$K_o(w) = \frac{P_o(t)}{U_o(t)} \quad \text{Equation 34}$$

where:
$P_o(t)$ is the force.
$U_o(t)$ is the displacement.
It is important to note that the force and displacement can be resolved into two components, one in phase and the other 90^o out of phase with the dynamic/harmonic load it is subjected to, hence could be shown as a complex equation, impedance could also be written as given in Equation 35.

$$K_O(w) = K_{o1}(w) + iK_{o2}(w) \quad \text{Equation 35}$$

where i is = $\sqrt{-1}$.
The real part of the Equation represents the soil stiffness and inertia, while the imaginary part of the equation represents the radiation and material damping. The impedance function of a system is very essential because it makes it possible to predict the resonant amplitude, resonant frequency, dynamic stiffness and natural frequency of the system which are core for analyzing the dynamic response of that system.
Even though most studies to calculate the impedance functions of systems tend to assume a massless soil,[2] suggested the use of models with mass by taking the spring stiffness to equal the static stiffness of the system, because the use of massless soils may result in stiffness being negative over large frequency ranges. Another assumption made is that under dynamic loading, the footing of the foundation is in constant contact with the soil, hence the displacement of the soil beneath the footing is taken to be equal to the displacement of the footing [26].

The vertical displacement amplitude of the system is given by the Equation 36.

$$U_v = \frac{P_o}{K_o - Mw^2 - iCw} \qquad \text{Equation 36}$$

where:
w is the excitation frequency.
K_o is the equivalence of static stiffness.
P_o is the vertical force.
M is the lumped mass of the footing.
C is the radiation damping coefficient of the system.

1.13 Effect of embedment

In practice, most foundations are not used as shallow foundations, most are usually embedded to a certain degree. The analysis of the effect of embedment to the dynamic response of the machine foundation has not gotten so much attention**, [**27] an analytical approach of estimating the dynamic response of embedded foundations, with the assumption that the underlying soil is divided into horizontal planes.

Their studies revealed that embedding a foundation tends to increase the stiffness and reduces the resonant displacement amplitude which in turn also leads to an increase in the resonant frequency of the system. Their analysis is based also on the determining the impedance functions (the stiffness and the damping coefficient) of the system.

The basic equation for the system is given by Equation 37.

$$M\ddot{U}(t) = P_v(t) - R_v(t) - N_v(t) \qquad \text{Equation 37}$$

where:
M is the mass of the foundation system.
Ü is the acceleration
$P_v(t)$ is the time dependent vertical excitation
$R_v(t)$is the vertical dynamic reaction at footing base.
$N_v(t)$ is the vertical dynamic reaction at the sides of the footing, this depends on the contact of the soil at the side of the footing.

In order to arrive at this equation, certain assumptions of an ideal situation had to be made, which includes but not limited to assumptions that the response of the foundation is elastic and propagated in a linear manner, also there is a perfect contact between the soil and the sides of the foundation as well as the excitation force acting along the vertical axis.

Since it is assumed that the underlying soil is an elastic half space, the established relationship that exists between the acceleration and the vertical dynamic reaction at the sides of the footing is shown as in Equation 38:

$$\frac{R_v(t)}{U_v(t)} = Gr_o(C_1 + iC_2) \qquad \text{Equation 38}$$

where, C_1 is a stiffness related function and is given in Equation 2.39:

$$C_1 = \frac{-f_1}{f_1^2 + f_2^2} \qquad \text{Equation 39}$$

And C_2 is related to the damping of the embedded system and is also given in Equation 40:

$$C_2 = \frac{f_2}{f_1^2 + f_2^2} \qquad \text{Equation 40}$$

f_1 and f_2 are frequency dependent displacement functions which were proposed by [12] as previously stated in the earlier part of this chapter.

The frequency dependent dynamic stiffness represented by k(w) is given by Equation 41:

$$k(w) = Gr_o\left(C_1 + \frac{G_s D_f}{Gr_o} S_1\right) \qquad \text{Equation 41}$$

The frequency dependent damping represented by is given c(w) by Equation 42:

$$c(w) = \frac{Gr_o}{w}\left(C_2 + \frac{G_s D_f}{Gr_o} S_2\right) \qquad \text{Equation 42}$$

where:
G_s is the shear modulus of adjacent soil.
D_f is the depth of embedment .
S_1 and S_2 are functions related to stiffness to damping.
The vertical amplitude of vibration is given by Equation 43:

$$U_v = \frac{P/k}{\sqrt{\left(1-\left(\frac{w}{w_o}\right)^2\right) + 4D\left(\left(\frac{w}{w_o}\right)^2\right)}} \qquad \text{Equation 43}$$

where:
P is the force.
k is the dynamic stiffness.

w is the forcing frequency.
w_o is natural frequency of the system.
D is the damping ratio.

1.14 Barkan's Method

[19] proposed a model for the analysis of foundations dynamic response. This method idealized the foundation to be a rigid lumped mass, and also the block to have an infinite stiffness, hence not considering any deformation that may occur internally[28]. This method gained widespread adoption and acceptance and was taken as an indian standard for the design and analysis of foundations under dynamic loading.
The soil in this model is represented as linear springs which are detailed in terms of soil properties such as the coefficient of elastic uniform compression, coefficient of elastic uniform shear [19].
It is represented mathematically as shown below Equation 44.

$$w_n = \sqrt{\frac{k}{m}} \qquad \text{Equation 44}$$

where:
w_n is the natural frequency of the body
k is the equivalent spring constant
m is the mass of the system.
and k is derived by Equation 45:

$$k = C_z . A_f \qquad \text{Equation 45}$$

where
and the amplitude of vibration is given by Equation 46:

$$U_v = \frac{\left(\frac{P_z}{k}\right) \sin w_m t}{1 - r^2} \qquad \text{Equation 46}$$

where r is given by Equation 2.48

$$r = \frac{w_m}{w_n} \qquad \text{Equation 47}$$

w_m is the operating frequency of the machine
P_z is the dynamic forces acting on the foundation.
[19]'s model although widely accepted has some notable shortcomings such as the fact that it does not take into account the damping effect in the system.
It does not also take into consideration the mass of the soil that might vibrate in phase with the soil, also it relies on estimates of the suggested spring value which is obtained from coefficient of the uniform elastic of compression.

1.15 Artificial Neural Network (ANN) Modelling.

Artificial neural networks as the name already suggests is a kind of predictive model model that is structured in a manner that mimics the human brain's pattern of data relay by neurons, it attempts to imitate these biological neurons for the purpose of data evaluation and pattern recognition by making use distributed of data nodes which are parallel implementation of non linear static dynamic systems. As a model, ANN have been observed to be a very reliable predictive tool over the years and one of the reasons that could be attributed to the fact that it tends to break down complex problems into simple processing units(neurons), these neurons forms clusters which are all inter connected by the means of layers. A common ANN model is usually made up of three layers, which are:

(i) The input layer.
(ii) A hidden pattern recognition layer.
(iii) The output layer.

A schematic of a simple ANN model is shown in Figure 6 below:

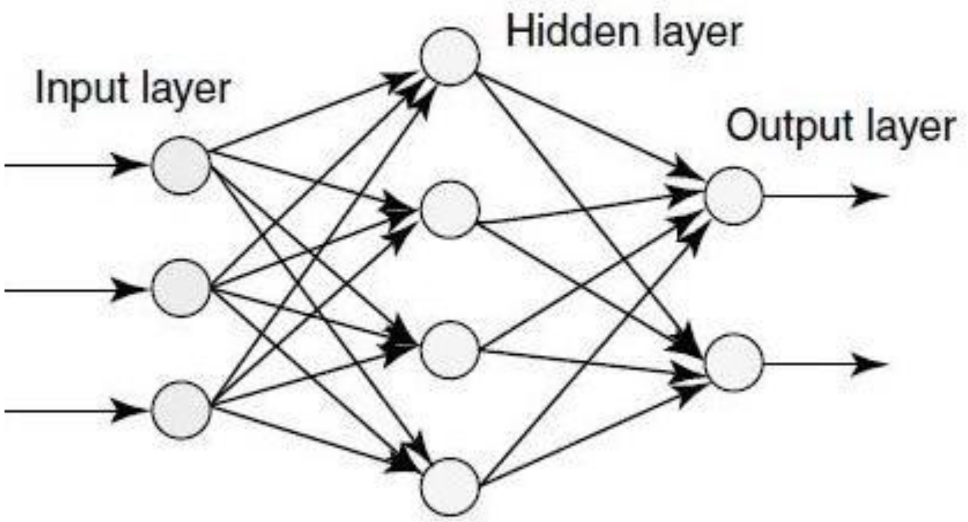

Figure 6 Schematic of a simple ANN model[29]

A typical neuron network model in practice is basically mathematical models defining a function f: X->Y or a distribution over x or both x and y is associated to a particular learning algorithm.
A connection between a pair of neurons has an associated numerical strength called synaptic weight or adaptive coefficient. The strength of interconnectivity can be represented as
a weight matrix with positive (excitory), negative (inhibitory), or zero (no connection) values**.** A graphic representation of the pattern of an ANN model is shown in Figure 7

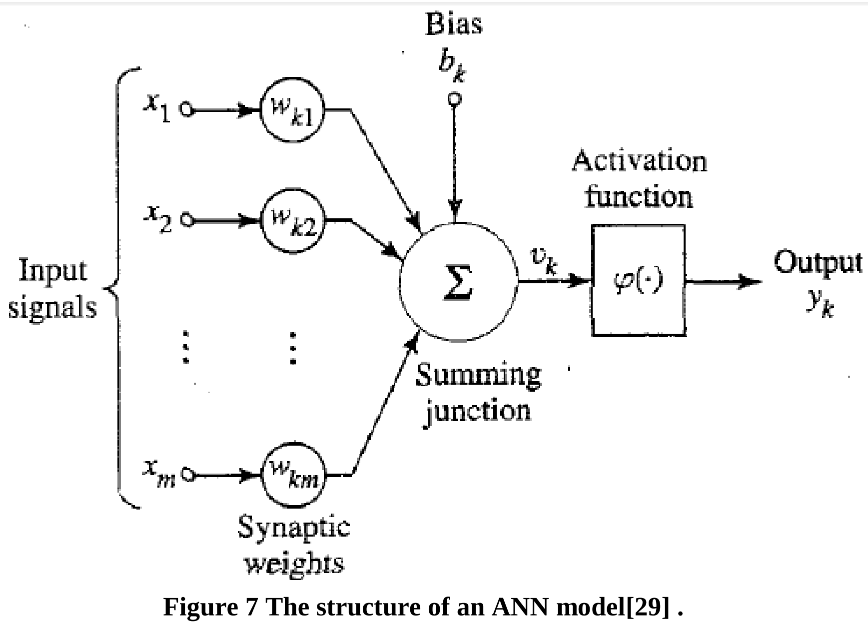

Figure 7 The structure of an ANN model[29] .

Different type of Neural Networks (NN) have been proposed but all of them have three things in common: the individual neuron, the connection between them (architecture), and the learning algorithm. Each type restricts the kind of connections that are possible. For example, it may specify that if one neuron is connected to another, then the second neuron cannot have another connection towards the first. The type of connection possible is generally referred to as the architecture **.** ANN could generally be classified into two, other types fall under this two broad classifications, and they are

(i) Feedback structure, also known as the recurrent ANN: In this type, the signal travels in both forward and backward directions, and this is achieved by the introduction of loops in the system.

(ii) Feed forward structure: In this type, the signal only moves in the forward direction as there is absence of any loops.

Figure 8 shows the general classification of ANN models.

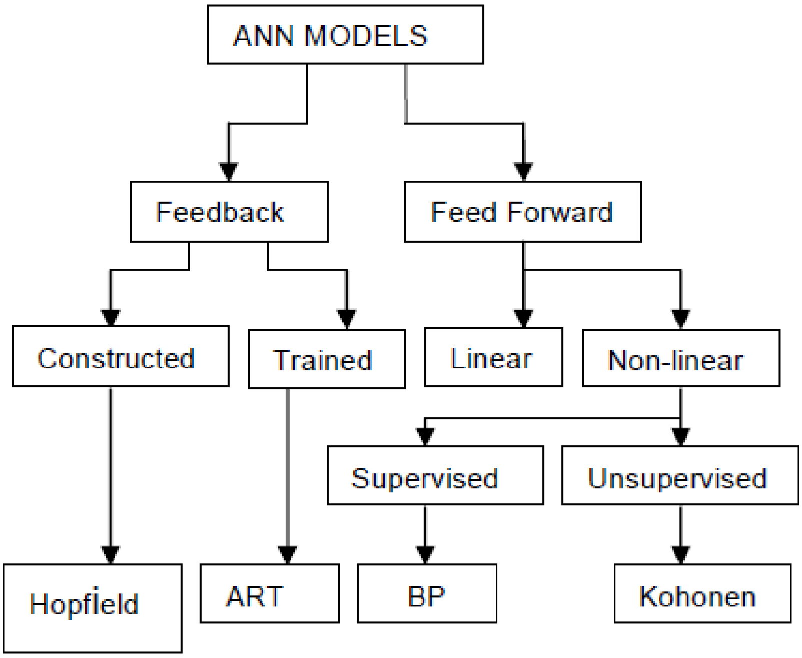

Figure 8: General classification of ANN models[31]

Advantages of ANNs

The ANN due to its structure is widely accepted and utilised by a lot of people due to some certain advantages it has over most other analytical tools, and they include:

(i) A neural networks posses the ability to learn how to carry out activities on its own, this is referred to as Adaptive Learning.

(ii) A neural network or ANN can create its own representation of the information it receives during learning.

(iii) In neural network or ANN computations can be carried out in parallel, that means it can compute data for real time activities.

(iv) Neural networks learn to recognize the patterns which exist in the data set. Pattern recognition is a powerful technique for the data security.

(v) ANN posses a good degree of flexibility, even though it takes a bit of time to adjust to changes.

(vi) They can be utilized for very complex data.

Limitations of ANN

The neural network system also has some Limitations. The limitations of ANN are:

1. ANN or Neural Networks is not a daily life problem solver.
2. There is no structured methodology available.
3. There is no single standardized paradigm for Neural Networks development.
4. The Output Quality of an ANN can be unpredictable.
5. Many ANN Systems does not describe how they solve the problems.
6. Nature of ANN is like a Black box.

Over the years different people have tried to come up with various methods and models from which to predict or ascertain the various dynamic response parameters of machine- foundation systems. The main variation in many of these models and methods is the way they tend to represent the soil medium, such as the representation as independent springs in the wrinkle model or as springs linked by an elastic medium as in the filanenko model etc.

One major finding is that most experiments tend to utilize different forms of excitation in testing such as using oscillators, but there seems to be none which utilized actual machine tools while carrying out machining operations and taking into account the dynamic forces at work.

II. Materials and Methods

It is very important to investigate the proposed site for the experiment, first to make sure that there are no environmental factors that would be hazardous over the course the study, and also to ascertain if the study would be a source of disruption to any of the vital activities in the location.

Also, one of the easily overlooked aspects in studies regarding dynamic response studies of foundations has been the properties of the soil underlying the foundation itself, as already discussed in the previous chapter, this is a very vital aspect of calculating the dynamic response of the foundations because to a considerable extent, the soil also dissipates part of the dynamic forces and hence an accurate study cannot be carried out without taking into account the vital soil parameters which includes the soil density, poisson's ratio and shear modulus. To this effect, soil samples should be subjected to the necessary tests to ascertain these values.

2.2 Casting of the foundation

[8] reported, one of the first parameters to be chosen in foundation design is the dimensions and this would depend on the machinery it is going to be carrying and this has to be done with the consideration that there has to be provision of ample space to accommodate the machine as well as for the operation of the machinery. The outline dimensions of the foundation is usually suggested by the machine producer[7], the depth of the foundation Would be chosen in a way the center of gravity of the system falls in the same plane.

Reinforced concrete is generally used for machine foundations for various reasons such as:

(i) It provides enough rigidity to support the usage of the machinery.
(ii) Its modulus of elasticity fall within acceptable range.
(iii) Reinforced concrete has a high compressive strength in comparison to most materials.
(iv) It is resistant to large amounts of tensile stress.
(v) Also it is fire and weather resistant to an extent.

Following [7] guidelines on designing a reinforced concrete machine foundation, the following procedures neeed be utilized:

(i) Taking into account the data provided by the machine producer: the producers of machines provide certain data in order to aid the designer of the foundation on what to be expected while running the machine, such data includes but not limited to the layout or geometry of the machine, the operating speeds of the machine, the permissible amplitude of vibrations etc. These data are to be considered in designing the foundation. These data could be found on machine body or internet searches could be utilized.

(ii) Make an assumption of a trial size for the foundation: as already stated earlier in this chapter, the outline dimensions for the foundation is usually suggested by the manufacturer, but other dimension like the minimum thickness needs to be ascertained based on certain factors such as the depth of embedment to be used if any and the bearing capacity of the material used for the machine foundation.

(iii) Using a dynamic response method to evaluate the natural frequency of the selected dimensions: here a method of dynamic analysis would be utilized to ascertain the natural frequency and ensure it doesn't coincide with that of the working frequency of the machine to prevent resonance.

In order to ensure proper strength of the concrete foundation, the following practice need be followed as outlined:

(i) The designer should ensure casting of the foundation in a single, continuous operation.
(ii) The reinforcement should be up to a standard density, usually a value not less than 25kg/m$^{3.}$
(iii) The reinforcement should be made from 12mm bars at a spacing of between 200milimeters to 250milimeters, and extend both vertically and horizontally.
(iv) Where bolts are provided for fitting the machine, it should be done via base plates fitted with anchor bolts, and the bolt holes should be back filled.
(v) The mixture should be at least M-15 reinforced concrete, and the aggregate top be used is gravel. The proportions for the mixture is shown in Table 1.

Table 1 : Different compositions and proportions of concrete mixture

Designation	Mix proportions (cement:sand:coarse aggregate)	Characteristic compressive strength in N/mm^2	Group
M5	1:5:10	5	Lean concrete
M7.5	1:4:8	7.5	
M10	1:3:6	10	Ordinary concrete
M15	1:2:4	15	Ordinary concrete
M20	1:15:3	20	
M30	1:1:2	25	Standard concrete
M40	Design mix	30	
M50		40	

Source: https://civilsir.com, 2017[32]

ANN model.
Artificial neural networks mimics the human brain in a bid to transfer data from one neuron to the other.
Neurons would represent the computing blocks of the model and various layers would consist of the required parameters such as the mass of the foundation, the soil spring constant and area of the foundation consisting the input layers, while the activation functions, normalization and weighting factors would make up the hidden layer. The output would be the amplitude of the vibration.
The architecture of a typical ANN model is shown in Figure 9.

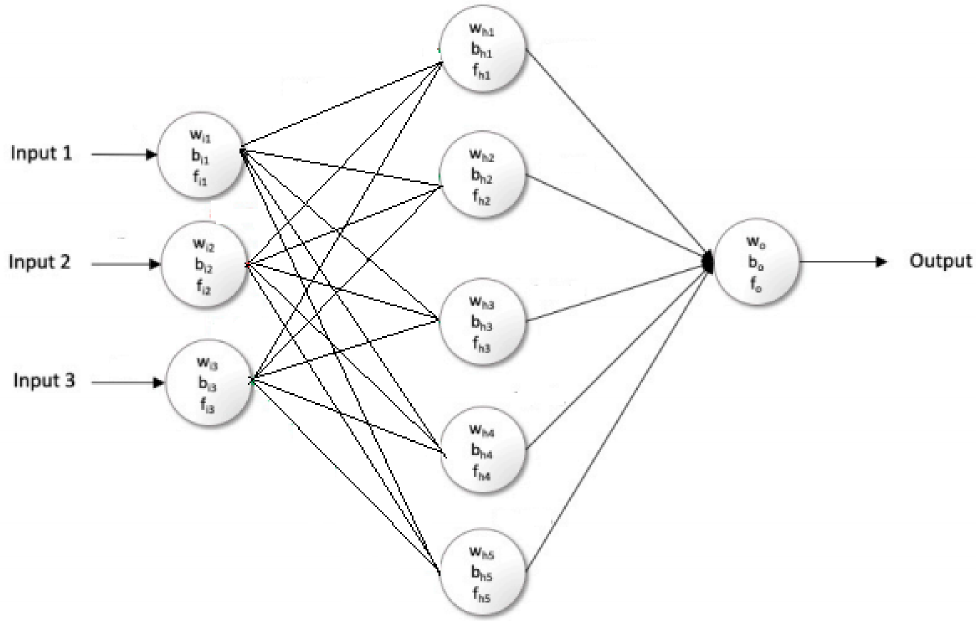

Figure 9: Architecture of the ANN model

Where ω represents the neuron weight of the neurons, b is the biases at each neuron, and f is the corresponding activating functions.
The subscript h shows the hidden layer, while the subscript o is for the output.

III. Conclusion

Artificial Neural Networks have promises in the dynamic response studies of machine tool foundations. ANN has the capacity to navigate the search modules and present many solutions. Importantly, since it can take many inputs and has many processing layers for refinement, it is obviously a practical leeway for solving demanding complex engineering problem, such as machine tool foundations problems. Concerted efforts are required to ensure good results are obtained and improvement made using ANN in this area.

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