METHODS OF EVALUATING THE EFFECTS OF TERRAIN GEOMETRY ON VEHICLE MOBILITY

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ABSTRACT

The requirement for operating combat vehicles at the highest possible speed over rough ground makes it important to be able to determine the effects of terrain geometry on allowable speed. A research program is being carried out which should lead to methods of analyzing this relationship. Data on character, location, and frequency of occurrence of terrain geometry is to be collected and organized. Methods of predicting the dynamic response of a proposed vehicle operating at various speeds over rough ground without the necessity of a full scale test on a pilot model have already been developed. These methods make use of electronic computers to simulate the response of the vehicle. From the simulation, data can be obtained concerning rotational and translational displacements, velocities, and accelerations of the vehicle and forces and stresses at various points in its suspension system or structure. This dynamic response data can be compared to suitable performance criteria to enable the designer to judge the suitability of the design in terms of structural strength, effectiveness of the human occupants, and the performance of certain components, such as the gun stabilization system. The effect of speed on this performance can also be judged.

The available tractive effort and external resistance to motion are other important factors affecting the mobility of a vehicle. Methods of computing these quantities from known vehicle characteristics and physical characteristics of the soil are already in use based on the assumption of even distribution of load on wheels or tracks. There are, however, a number of situations, for example, operation on a slope or over a vertical obstacle, where the terrain geometry produces non-uniform load distribution. To deal with these situations, an extension of the present analytical method is required. Mathematical techniques for accomplishing this analysis are discussed briefly both for steady-state conditions and for the dynamic case of continuous motion over soft, rough ground.

METHODS OF EVALUATING THE EFFECTS OF TERRAIN GEOMETRY ON VEHICLE MOBILITY.

1. Introduction

In the development of combat vehicles to meet constantly changing military needs, those aspects of design dealing with the effects of off-the-road operation of vehicles have in many respects been based on the use of data and information arrived at by "cut and try" methods. The lack of sufficient basic research has limited the designer's ability to know the direction in which vehicle design must move to make significant improvements in performance or to predict this performance for specific designs in advance of full-scale tests.

A general statement of the requirements for a successful analysis of vehicle mobility has already been presented by Bekker.[1] He has pointed out that there is need for "a generalized approach to a solution based on a systematic, quantitative evaluation of the relationship between a vehicle and the environment of vehicle movement, i.e., soil structure and terrain configuration. Given the vehicle's technical characteristics, the mechanical properties of the soil, and the geometry of the terrain surface, the operational limits of any type of real or imagined vehicle can be predicted".

In an attempt to find effective methods of analyzing the relationship between cross-country vehicles and the geometry of the terrain surface, the Willow Run Research Center of the University of Michigan has for several years been engaged in a research program in this field sponsored by the Detroit Arsenal. It is the intention of this paper to outline our concept of the problem and certain suggested methods of solution. Some of these suggested methods are actively being developed, and the progress obtained so far on the various phases of the program will be indicated here.

In discussing the effect of terrain geometry on vehicle performance, it is convenient to think of the trafficability of a particular section of terrain as being described by one of several classifications. A section of ground may be completely impassable if the vehicle cannot take any route which avoids excessive slopes, irregularities (such as cliffs, ditches, or ravines), or obstacles (such as trees or tank traps). A section of ground may be considered completely passable if it consists of level or gently-rolling ground with substantially no areas representing islands of impassability. Finally, a section of ground may be considered partially passable, meaning that it can be traversed only at speeds slower than the maximum available vehicle speed. This reduction in speed may be necessitated by the requirement for threading through islands of impassability or by the fact that the ground is sufficiently rough over its entire surface as to require reduced speed in negotiating it.

The importance of the study of vehicle operation over partially passable territory is being increased by the tactical and strategic requirements for higher vehicle operating speeds. These requirements for higher speed are intended to lead to the achievement of tactical surprise and operational flexibility, as well as minimizing the exposure of the vehicle to enemy action. The situation of partial passability is, therefore, one of great importance but one which is very difficult to deal with analytically.

The study of resistance to motion and available tractive effort is also of importance. Methods of determining these quantities from known vehicle characteristics and physical characteristics of the soil are already available based on the assumption of even distribution of load on wheels or tracks. There are, however, a number of situations, for example, operation on a slope or over a vertical obstacle, where the terrain geometry produces non-uniform load distribution. To deal with these situations, an extension of the present analytical methods is required.

Methods of determining allowable speed over partially passable territory, and resistance to motion and available tractive effort for the case of non-uniform load distribution are discussed in this paper. The treatment of these problems is in many respects a logical extension of the basic concepts and technical material presented in Reference 1.

2. Proposed Methods of Analysis for Conditions of Partial Passability

The problem of developing methods of analyzing the effect of terrain geometry on allowable speed for conditions of partial passability may be logically divided into three parts:

a. Data must be collected on terrain geometry in sufficient quantity and over a wide enough spread of geographical locations and geological conditions that the terrain can be classified as to specific character, location, and frequency of occurrence.

b. Methods must be devised for predicting the dynamic response of a specific vehicle over a specific section of ground at various speeds. These methods must be quantitative and must provide information in such form that the suitability of the vehicle's performance may be determined.

c. Criteria must be adopted by which the suitability of the performance of a vehicle may be judged on the basis of its dynamic response. The undesirable effects of excessive speed on performance are of several types. First, physical damage to the suspension system, structural components, or equipment may occur. Second, excessively rough ride may cause personnel fatigue and associated reduction in combat effectiveness, or may even cause injury. Finally, a rough ride may interfere with operations being performed while the vehicle is in motion, such as driving, observation, gun loading, and gun-laying. In the case of vehicles which incorporate gun stabilization systems, the accuracy of gunfire can be materially affected by vehicle motion.

2.1 Terrain Measurement

In order to obtain information on the basis of which terrain geometry may be characterized as to type, location, and frequency of occurrence, a program is being initiated at the Willow Run Research Center which will lead to the collection of data on terrain geometry in various geographical locations. Since it is contemplated that large amounts of data must be collected, it will be necessary to provide a type of measuring device capable of obtaining the data with sufficient accuracy and with a reasonable expenditure of time and effort. As the first step in the program, we are therefore undertaking the development of a terrain profile measuring system. This will probably take the form of a small vehicle which can be rolled over the ground to be measured and which will carry special instruments for automatically recording the vertical position of the ground surface as a function of horizontal position. Once these data have been collected, they will be analyzed with the intention of reducing them to a relatively few types of section which may be used as standards for vehicle design and performance analysis.

Although the method of organizing terrain geometry into specific categories cannot be firmly established at this time, it is possible to speculate on methods which might be used. If the particular section of ground under consideration is rolling ground having substantially sinusoidal cross-section within a narrow range of wave lengths, it would be possible to consider it equivalent to a purely sinusoidal profile of a specific wave length and amplitude. Within certain limits of amplitude and frequency, the motion of the vehicle will remain within the linear range of the suspension system. In this case, the hull motion will also be simusoidal and at the same frequency as the disturbing function due to the road. This situation can be analyzed mathematically to provide amplitudes of pitch and of vertical motion at any point in the tank. The vertical motion amplitude and its related frequency can then be converted to an indication of ride behavior by reference to certain standards discussed in Section 2.3.

If the terrain contour is predominantly sinusoidal but of an amplitude sufficient to result in operation of the suspension system outside its linear range, it would be possible to compute the hull response as a non-sinusoidal periodic function. However, it is unrealistic to consider this case as one for which the dynamic response is a purely periodic function. The unsatisfactory ride characteristics resulting from traveling over sinusoidal ground are primarily due to the build-up of a resonant condition. But since the road is not a perfect sine wave and since the driver will control the speed to avoid excessive shock, the amplitude of motion will be variable. It will therefore be necessary to analyze the condition by more involved techniques.

To arrive at some standard to represent this type of road, it will probably be advisable to determine the dynamic response of typical vehicles by simulation means (See Section 2.2) and then to attempt to correlate this response with some mathematical representation of the terrain contour such as might be obtained by Fourier analysis or by autocorrelation methods.

In addition to sinusoidal characteristics, terrain profiles are likely to contain specific irregularities which are rather easily described. Vehicle dynamic response can be definitely determined for a bump of specified dimensions, so that a standard terrain section could be defined as containing irregularities of specified size and shape at definite frequencies of occurrence. Bekker has suggested[1] that each type of irregularity be represented by parameters corresponding to its important dimensions. A vertical obstacle, for example, would be described by its height, h_v. A horizontal obstacle (such as a ditch) would be described by its depth, h_v, and length, l_d. Following this approach, other parameters could be assigned to more complicated irregularities, as necessary.

2.2 Determination of Vehicle Response

The process of determining vehicle performance can, of course, take place by means of tests of real vehicles over what have been selected as standard sections of rough ground. The time and expense for such test procedures and the impossibility of using them prior to the existence of a pilot model makes it desirable to use some other method for determining performance. A method which appears to be ideally suited for this purpose has been under development at the Willow Run Research Center for several years; this method involves the use of the analog computer[2] for obtaining the dynamic response of a vehicle.[3,4] In using an electronic computer for this purpose, the process used is essentially one of simulation. By this it is meant that the computer acts as a model of the tank, the dynamic response of the computer being for all practical purposes identical with that of the tank.

As a basis for computing the response of the vehicle, it is represented schematically as shown in Figure 1. (The present discussion is confined to the motion of the vehicle in the pitch plane only.) The hull of the vehicle is considered as a rigid mass capable of pitching and bouncing. A number of road wheels are attached to it by means of a set of springs and damping devices which represent the springs, bump stops, and shock absorbers of the suspension system. The wheels are considered as masses capable of moving parallel to the yaw axis of the vehicle. Each wheel is supported above the ground by means of a spring and damping device representing the characteristics of the rubber tire and track. Since each spring is non-linear, the term k_i representing the force exerted by the spring is a non-linear function of its length. Similarly, the term c_i is a non-linear function of the time rate of change of length of each damping device. Deflection of the soil under load can also be allowed for, if required, by using an equation of the form

$$p = kz^n \tag{1}$$

where p is the unit load in lbs. per sq. in. exerted by each wheel on the ground, z is the sinkage of the wheel in inches, and k is the modulus of deformation. Using this representation of the vehicle and soil, equations can be written based on Newton's laws of motion to describe the motion of the various elements of the system when subjected to disturbances such as the effect of traveling over rough roads. These equations are then set up on the computer so that specific numerical solutions may be obtained. If, for example, input voltages are supplied to the computer representing the varying vertical ordinates of the road under each of the road wheels as the vehicle moves over rough ground, the computer will provide output voltages indicating, as a function of time, the pitch and bounce of the hull and also the vertical motion of each of the road wheels. The computer can indicate not only displacements, velocities, and accelerations, but also forces and stresses at various points in the vehicle.

In Figure 2 an example is given of the type of data obtainable from a suspension system simulation. This figure shows the response of an M47 tank as it moves over a 12 inch by 12 inch square timber at a speed of 10 feet per second.

Stresses in suspension structural components, such as road arms, volute springs, or the frame of the hull, may be computed from the curves. These have maximum values at the instant when the hull bottoms on the first road wheel. Figure 2a indicates a peak value of spring force at Roadwheel No. 1 (including the effect of torsion bar, volute spring, and bump stop) amounting to 133,000 lbs. It is also possible to infer the magnitude of stresses occurring in such items as mounting brackets or electronic components from the values of maximum acceleration occurring at the appropriate point in the hull. Figure 2b indicates a peak value of vertical acceleration at a point in the hull above the first wheel amounting to 220 ft/sec^2 or 6.8 g.. In determining allowable stresses in a member, the effect of fatigue must be considered. Information on this could be made available from the simulation by noting frequency of occurrence of stresses exceeding a given magnitude for each mile of travel over any assumed section of terrain profile.

The ride behavior of the tank can also be determined. Ride behavior is defined as the effect of the hull motion on the comfort and performance of the operating personnel. Plots of pitch and bounce in terms of displacement, velocity, and acceleration at any position in the hull can be obtained (see Figures 2c, 2d, 2e, and 2f), and, as shown in Section 2.3, these can be interpreted in such a way as to indicate the effect on personnel in producing fatigue over long periods of time or in interfering with the ability of the personnel to perform tasks while the tank is in motion.

Simulation techniques have also been used in analyzing the performance of other components of the vehicle. For example, by coupling a gun stabilization system simulation to a suspension system simulation, the effect on stabilization system error due to traveling over rough ground has been studied. The development of analog computer techniques has already reached a stage where useful design and performance data can be provided. However, this development must be continued if the full potentialities of the method are to be realized. There is need for collecting more accurate information on the characteristics of vehicle components and materials. The mathematical analysis of the mechanics of suspension systems must be extended to deal with the effect of longitudinal forces, such as the tractive effort of the engine or the recoil forces caused by gunfire, and to deal with roll motions. Also, there is need for the development of special-purpose components of analog computer equipment. For example, a more universal "road function generator" must be developed which will be capable of introducing voltages into the computer representing the complex terrain profiles which will be determined during the terrain data collection program.

2.3 Establishment of Performance Criteria

In order to interpret properly the response data obtained from vehicle simulation, it is necessary to establish criteria on the basis of which performance may be judged. The matter of arriving at acceptable levels of stress in the vehicle structure should not be difficult since allowable stresses are a matter of straightforward engineering design. With respect to allowable shock loading of components carried aboard a vehicle (particularly electrical and electronic components), much work is being done by various organizations.[5] The primary need, therefore, is for the collection and analysis of information already available. The required performance of gun stabilization systems is a matter for detailed study of the tactical requirements of such systems. Eventually, performance criteria should be established in terms of gunlaying error when traveling over specified ground at specified speed.

With respect to the effect of hull disturbances on personnel, there is need for more factual data. A number of investigators have studied the effect of various types of motion on passenger comfort. These independent investigations were collected and analyzed by the Riding Comfort Research Committee of the Society of Automotive Engineers and have led to the use of a generally accepted curve, giving the relationship between frequency and amplitude of vertical sinusoidal motion corresponding to an acceptable ride (see Figure 3).[6,7]

While this information is of value, its usefulness is limited by the fact that it covers only sinusoidal motion and that it is concerned with standards of ride performance more exacting than those under which cross-country vehicles must operate. Specifically, the recommended limit curve of Figure 3 corresponds to a level "which should be well within the comfort range for even the most sensitive person".[7]

A direct approach to the problem of establishing ride standards suitable for combat vehicles would be to conduct field tests. In doing this, representative vehicles would be run over various test courses at various speeds. These vehicles would carry instruments, such as accelerometers, capable of indicating hull motion. By relating measured data to the subjective observations of test personnel riding in the vehicle, it should be possible to arrive at standards of allowable hull motion.

An additional method which would obtain basic data under more carefully controlled conditions would be to construct a special device, consisting of a test seat whose motion could be controlled in bounce, pitch, yaw, and roll. By subjecting test personnel to motion of various types, both sinusoidal and non-sinusoidal, it would then be possible to assemble the data necessary for the adoption of standards of riding comfort suitable for combat vehicles. Construction of such a device is under active consideration by the Detroit Arsenal.

3. Determination of Available Tractive Effort

In addition to the allowable speed of a vehicle as affected by terrain geometry, another characteristic of great interest is the maximum tractive effort available. The available tractive effort must, for specified combinations of conditions, be at least equal to the required tractive effort, T_r, as determined by the following equation:

$$T_r = F_h + W \sin \theta + \frac{W}{g} a \qquad (2)$$

where W is the weight of the vehicle, lbs; F_h the external resistance to motion (due to the physical characteristics of the soil), lbs; θ the angle of the slope which it must ascend; and a the acceleration, ft. per sec. per sec. If the vehicle is towing an additional unit, the equation must of course be interpreted so as to include this effect.

Maximum tractive effort which can be developed at the driving wheels may be limited either by the maximum force which can be produced by the engine less the friction of the transmission system or by the maximum tractive effort which can be developed between the driving wheels or tracks and the soil. Since maximum tractive effort which can be produced by a given engine and transmission system can be computed without difficulty, it is the problem of determining the tractive effort limitation imposed by the soil characteristics which is of primary concern here.

Analyses of available tractive effort have in the past been confined largely to conditions existing on level ground for constant pressure distribution. The computation of these quantities becomes considerably more complex if the vehicle is operating over non-level ground. This added complexity is due to the fact that the loading varies among the individual roadwheels and is not constant with respect to time. Variation of loading between roadwheels exists even for operation on a smooth slope. This variation in load distribution affects not only the maximum tractive effort which can be developed but also the external resistance to motion. Thus, problems involving tractive effort involve complex relationships between the characteristics of the vehicle and the physical and geometrical characteristics of the soil. The development of suitable methods of computing these quantities will require both theoretical analysis and experimental verification. It is outside the scope of this paper to develop specific design methods and formulas to be used for this purpose, but the general method of attacking the problem can be suggested by discussing specific cases.

The method of determining the capability of a wheeled vehicle with low-pressure tires in ascending a slope will be considered first. The maximum tractive effort which can be developed by each driving wheel is

$$T = b\ s\ (c + p \tan \phi) \qquad (3)$$

where b is width of wheel, in.; s is ground contact length of wheel, in.; c is coefficient of cohesion of soil, lb. per sq. in.; ϕ is angle of friction developed along the shearing surface of the soil, lb. per sq. in.; and p is ground pressure, lb. per sq. in.

The total load on the wheel is, to a close approximation,

$$F_W = b\ s\ p. \qquad (4)$$

Therefore,

$$T = F_W \left(\frac{c}{p} + \tan \phi\right) \qquad (5)$$

Since the load distribution among the wheels is not uniform, it must be calculated by applying the laws of classical mechanics to the components of the vehicle. The method of calculation does not differ in principle from those discussed in Section 2.2, except that it is a steady state rather than a dynamic solution. The details of the computation need not be described here. The total tractive effort is then

$$
\begin{aligned}
T_a &= \Sigma F_w \left(\frac{c}{p} + \tan \phi\right) \\
&= \left(\frac{c}{p} + \tan \phi\right) \Sigma F_w \qquad (6)
\end{aligned}
$$

where the summation of F_w is for the driving wheels only.

The available tractive effort is to be compared to the required tractive effort as given by Equation 2. For purposes of illustration, the term F_h in this equation will be assumed to be due only to soil compaction perpendicular to the surface of the slope. If the sinkage of the soil, z, is given by Equation 1, with the value of n assumed equal to 1, then it can be shown that

$$
F_h = \frac{F_w p}{2sk} = \frac{bp^2}{2k} \qquad (7)
$$

If the acceleration is assumed to be zero, the criterion for acceptable performance is that

$$
\left(\frac{c}{p} + \tan \phi\right) \Sigma F_w = \frac{bp^2}{2k} + W \sin \theta \qquad (8)
$$

The preceding development is typical of the approach to be used for analysis of the tractive capabilities of a static vehicle where wheel slippage need not be considered. The treatment of the problem of determining the tractive effort of a moving vehicle when slippage is occurring is considerably more involved. A basis for the computation is the following equation:

$$
T_a = b \int_o^s (c + p \tan \phi) \left[\frac{e^{(-K_2 + \sqrt{K_2^2 - 1})K_1 j} - e^{(-K_2 - \sqrt{K_2^2 - 1})K_1 j}}{y_{max}} \right] dx \qquad (9)
$$

where T_a is total tractive effort, lbs.; c, ϕ, K_1, and K_2 represent physical characteristics of the soil, y_{max} is the maximum value of the numerator of the bracketed quantity, j is soil strain, in.; and x is longitudinal position along the track or wheel. In the most general case, p and j may be functions of x, while s is a function of p and therefore indirectly a function of x. For steady state conditions (e.g., constant speed over level ground), there should be no special difficulty in evaluating the integral of Equation 9. If the amount of numerical computation required for detailed studies becomes burdensome, electronic computing techniques can be employed.

The computation methods so far described in this section are capable of providing data on the relationship between available and required tractive effort for cases of non-uniform load distribution under steady-state conditions. It may be desirable to extend these methods of computation to allow the analysis of dynamic conditions occurring when the vehicle travels over soft, rough ground. This would provide information relating to peak values of ground pressure, limitations placed on maximum attainable speed by the physical characteristics of the soil and the geometry of the terrain, and tractive power input requirements and efficiency.

The methods of solution to be employed for such studies would have to be consierably more involved than those previously discussed. As an example of the approach to be used, the case of motion over soft, rough ground of a wheeled vehicle using low-pressure tires will be considered.

For each wheel, Equation 9 can be solved to obtain total tractive effort equal to:

$$T_a = \frac{b\ (c + p \tan \emptyset)}{K_1\ y_{max}\ i_o} \left[\frac{e^{(-K_2 + \sqrt{K_2^2 - 1})K_1\ i_o s} - 1}{-K_2 + \sqrt{K_2^2 - 1}} - \frac{e^{(-K_2 - \sqrt{K_2^2 - 1})\ K_1\ i_o s} - 1}{-K_2 - \sqrt{K_2^2 - 1}} \right] \qquad (10)$$

For our purposes this may be reduced to the more general form:

$$T_a = C_1 \frac{(c + p \tan \emptyset)}{i_o} f\ (i_o s) \qquad (11)$$

where i_o is slippage.

The ground pressure of pneumatic tires will remain substantially independent of load; therefore, p is a constant. The ground contact length, however, may be assumed to vary with total load:

$$s = C_2\ F_w, \qquad (12)$$

where F_w is the wheel load. The slippage, in per unit terms, is

$$i_o = \frac{v_t - v_a}{v_t} \qquad (13)$$

where v_t is the theoretical velocity based on wheel rotational speed, and v_a is actual velocity. Therefore,

$$T_a = C_1\ (c + p \tan \emptyset) \left[\frac{v_t}{v_t - v_a} \right] f \left(\frac{C_2\ F_w\ (v_t - v_a)}{v_t} \right) \qquad (14)$$

When traveling over non-level ground, F_w, v_t, and v_a may vary with time. To obtain a general solution to the problem, it is therefore necessary to determine these quantities for substitution into Equation 14.

It has already been noted in Section 2.2 that simulation methods can provide a continuous indication of wheel loading, F_w, as a function of time. By applying these methods to obtain the dynamic response of the vehicle in the longitudinal direction, it is also possible to obtain v_a as a function of time. The basic equation for determining longitudinal motion is

$$v_a = v_{a-o} + \int_0^t a\,dt = v_{a-o} + \frac{g}{W}\int_0^t (\sum T_a - F_h - W \sin \theta)dt \qquad (15)$$

If the basic mode of operation is to maintain a constant speed along the ground, the simulation would then be set up to control v_t, the theoretical speed (proportional to the engine speed) so as to maintain v_a constant. The most realistic means of doing this would be to provide a human "driver" who would manually control the engine throttle.

The analysis of tractive effort for the case of a moving tracklaying vehicle is more complicated, but a brief analysis indicates that these complications can probably be resolved, so that the same basic methods described above can be used.

4. Conclusion

It should be emphasized that the development of the analytical methods described in this paper will require a considerable research effort. This research must be directed toward (a) obtaining more data on soil characteristics and vehicle-soil relationships (b) developing and improving techniques of computing the effect of terrain geometry on vehicle response, and (c) determining criteria against which vehicle performance during cross-country operation can be judged. But these methods, once developed, could be of great use in assisting the process of developing and using future vehicles of superior performance.

References

1. ORO-T-247, "Methods of Evaluation of Off-the Road Locomotion", M. G. Bekker, Operations Research Office, John Hopkins University (August 17, 1953).

2. "Electronic Analog Computers", G. A. Korn and T. M. Korn, McGraw-Hill Book Co., Inc., (1952).

3. "Electronic Simulation as an Aid to the Design of Vehicle Suspension Systems", A. Lange and J. Dute, paper presented at the SAE National Passenger Car, Body, and Materials Meeting, Detroit, Michigan (May 4-6 1952).

4. 2023-2-T, "Analysis of the Suspension System of the M47 Tank by Means of Simulation Techniques", I. J. Sattinger, E. B. Therkelsen, C. Garelis, and V. H. Geyer, University of Michigan, Willow Run Research Center (June 1954)

5. 2145-4-P, "Shock on Electrical Components in Track Laying and Wheeled Vehicles", H. S. Bull, University of Michigan, Electrical Engineering Dept. (July 1954)

6. "Vehicle Vibration Limits to Fit the Passenger", R. N. Janeway, Chrysler Corporation, paper presented at the SAE National Passenger Car and Production Meeting, Detroit, Michigan (March 3-5, 1948).

7. "Ride and Vibration Data", SAE Special Publication SP-6 (1950).

Note–Reference position of hull and each wheel is vertical position of each item if tank were resting on level ground and had no weight.

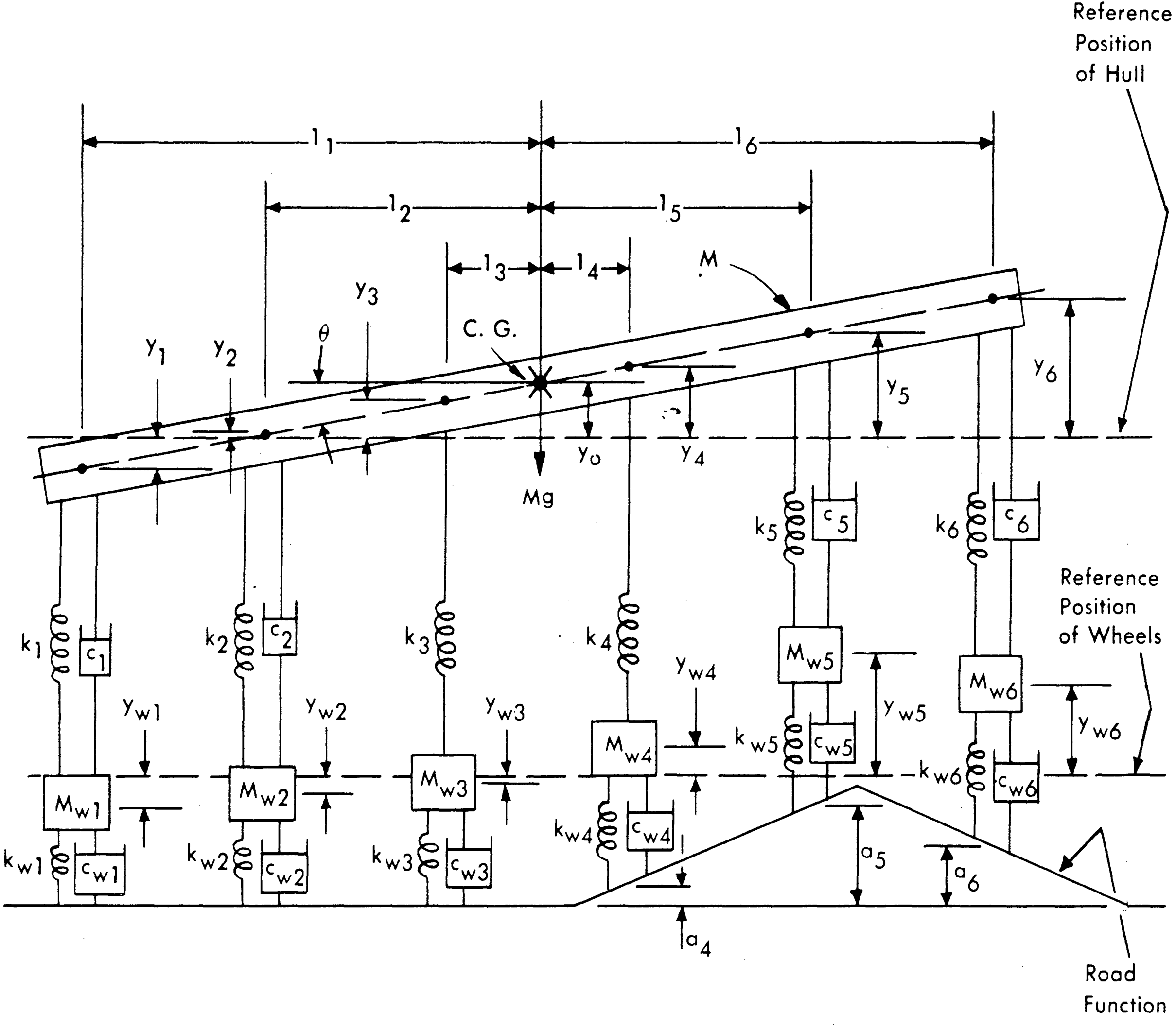

FIG. 1 SCHEMATIC REPRESENTATION OF TANK SUSPENSION SYSTEM

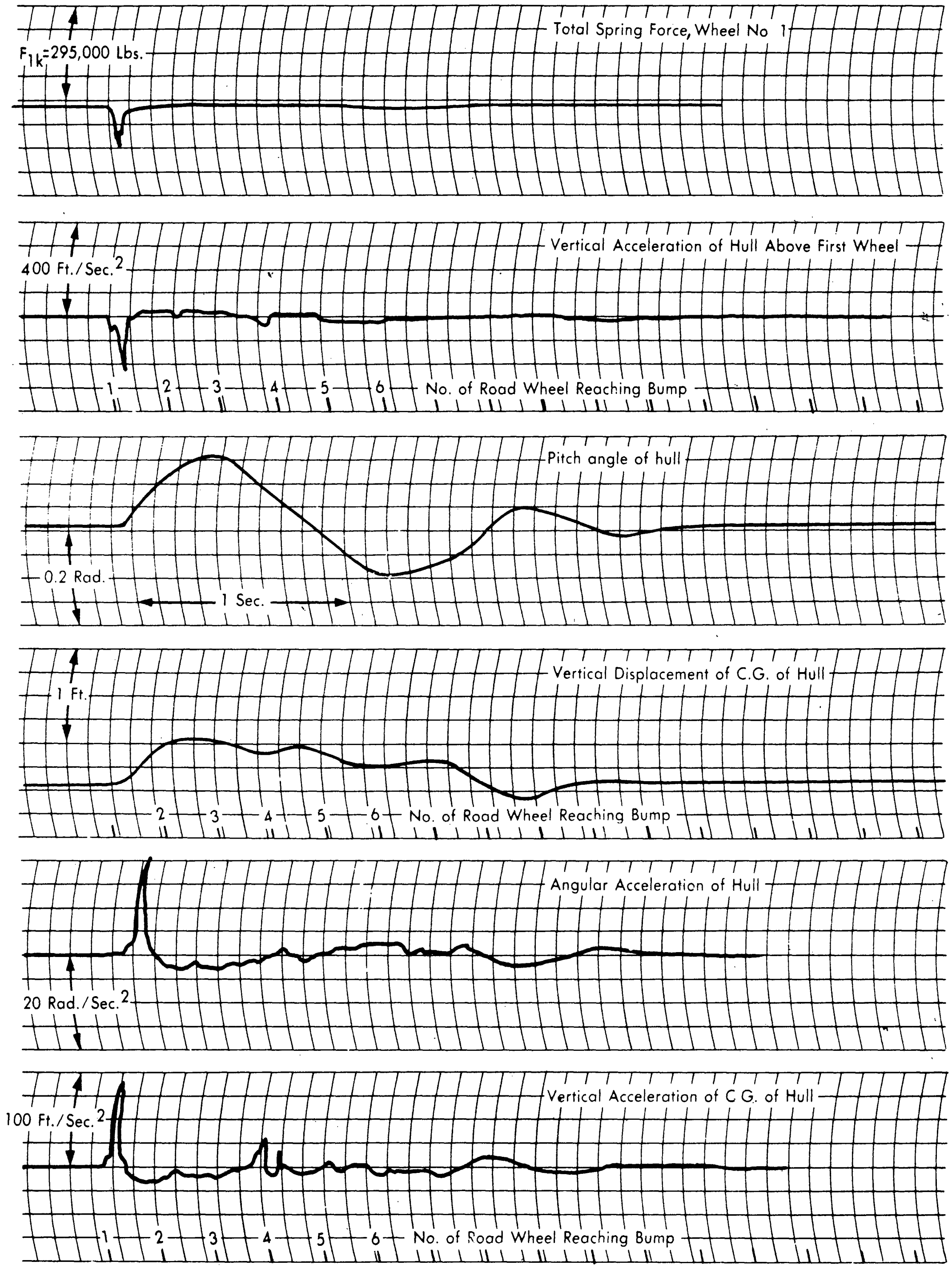

FIG. 2 SIMULATED RESPONSE OF M47 (12 inch Square Bump, Tank Speed of 10 fps)

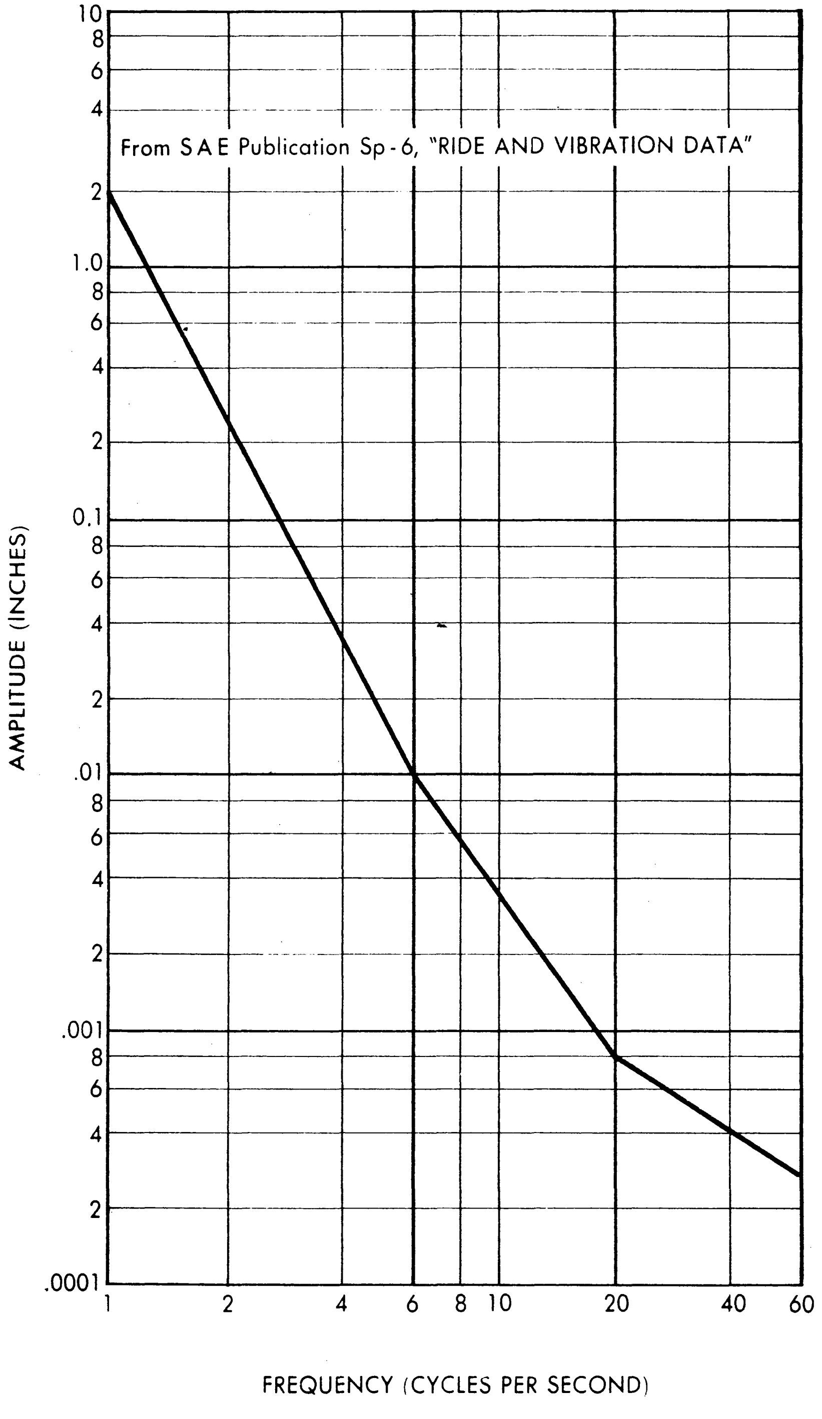

FIG. 3 RECOMMENDED LIMITS OF AMPLITUDE AND FREQUENCY OF SINUSOIDAL VERTICAL MOTION