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VIBRATORY LOCOMOTION REVISITED

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Abstract: Vibratory Locomotion is an old unused method of moving over terrain we invented at the Naval Civil Engineering Laboratory over 25 years ago. The patent [1] has expired. We had great hopes for it, but they never materialized. It is being presented here to remind readers it exists in hope that someone will find an application for it. The paper describes some applications, presents a simplified design method for the devices, and discusses the effectiveness of several vibratory locomotion prototypes we built and tested.

Key Words: Reciprocators; oscillator; skid; vibratory locomotion

INTRODUCTION:

The method uses a reciprocating weight to cause an object to incrementally slide or shuffle over the ground surface. It becomes perfectly reasonable to mount the weight inside a box, and have the box shuffle over the ground surface, and equally reasonable to put the reciprocating weight inside a boat and have the boat shuffle across the beach. An oscillating mass can be fixed to skids in place of the tracks on a bulldozer and make a different kind of a tractor. The peak drawbar pull of such a tractor is twice the product of its weight and local coefficient of friction. Our work demonstrated all of this and provided a detailed theoretical analysis that proved it all had to be true.

First of all, vibratory locomotion is a method for accomplishing land locomotion by causing a mass to reciprocate, back and forth, in a straight line that is inclined horizontally. To visualize the concept, imagine a skid that contains machinery that can reciprocate a heavy weight back and forth. The path of the weight's motion, viewed from aboard the skid, is a straight line inclined at 45 degrees for example, the path is such that the weight moves up and forward, down and backward as shown in Figure 1. When shaken at appropriate amplitude, the weight provides reaction forces on the skid that lifts and slides it along the ground. Specifically, when the weight is at the top of its stroke it lifts the skid and slides it forward; at the bottom of the stroke it is pushing downward and backward on the skid, but since the downward force increases friction, no back sliding takes place. The net result is a forward shuffling motion of the skid. Control of the skid can be accomplished by using two reciprocators, one on each side, and controlling the forward thrust of each. If one reciprocator is thrusting forward and the other aft, the skid can pivot about its center. One application considered was to propel a large solid concrete barge over a road for mine clearing. Figure 2 is a conceptual drawing of this idea.

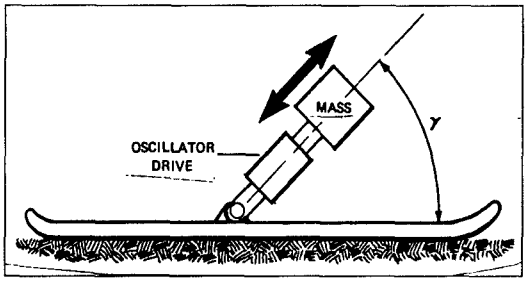

Figure 1. The vibratory locomotion concept.

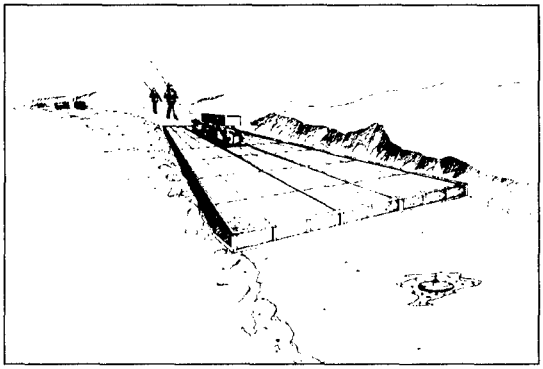

Figure 2. A massive concrete barge for mine clearing propelled by vibratory locomotion.

DEVICES BUILT AND TESTED:

After we completed the theoretical analysis, which we'll discuss later, we designed and built several prototype models to test the locomotion and drawbar pull capabilities. The first was a rocker crank oscillator with a 100-pound weight shown in Figure 3. It worked well and was the test skid used to provide the data for the published theoretical study [2]. This skid was tested in the arctic at Point Barrow and performed quite well. We tested several bottom configurations and the smooth bottom worked best. A compressed air bin shaker vibrator shown in Figure 4 also powered this small skid. The idea of a heavy piston vibrating inside a cylinder made the concept very compact and safe, especially compared to counter rotating eccentrics which are convenient but dangerous.

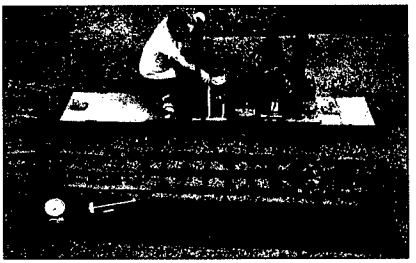

Figure 3. The crank rocker oscillator on the small skid with various cleat bottom arrangements for snow testing.

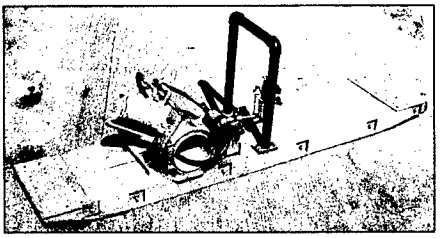

Figure 4. A small skid with a compressed air vibrator to accomplish vibratory locomotion.

We also built a large skid with a spring-supported platform (Figure 5). It was first powered by a resonant spring oscillator. A hydraulic motor rotated an eccentric weight to excite the resonant vibration, which smoothly propelled the large skid. Unlike the rocker crank oscillator it was easy to change the shake angle of the oscillator.

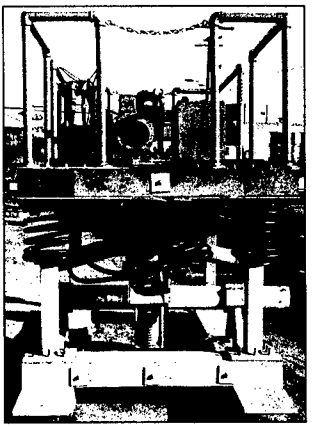

Figure 5. The large skid with a spring supported platform and a resonant spring oscillator. The engine powered a hydraulic pump to energize the hydraulic motor exciting the vibrating mass.

We also powered the big skid with our most versatile oscillator, a concentric shaft, counter-rotating eccentric oscillator with a phase or shake angle changer. A car differential was used to change the phase or shake angle (Figure 6). The oscillator on the skid is shown in Figure 7. The skid could climb modest hills and could tow a half-ton Navy pickup truck with its wheels locked. Once while touring the Navy Lab, a group of about 15 children was invited to climb aboard the skid for a ride, which they thoroughly enjoyed. The ungainly big skid made the 11 o'clock news nationwide one night. It

always attracted attention as we drove it around the compound. Even though it had only one oscillator it could be slowly steered or turned by shifting your weight to the desired turning direction.

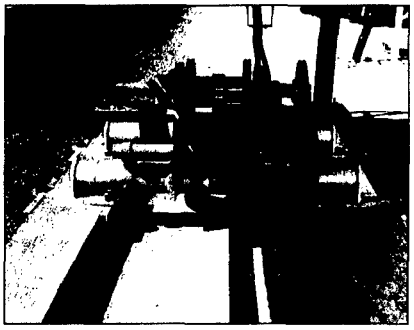

Figure 6. The concentric shaft counter rotating oscillator. The center weight turns in the opposite of the two outer weights. The drive shaft coming out of the differential is for changing the shake angle.

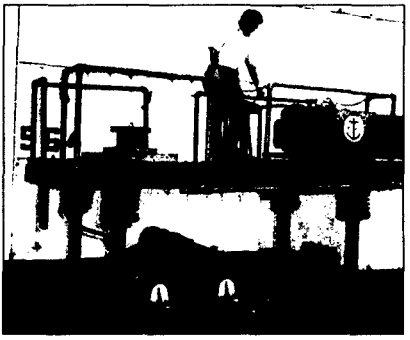

Figure 7. The large skid with the concentric counter rotating oscillator

We called one of the uses we proposed for the technology, the Beach and Launch Unit. The concept was to provide Marine landing craft with capabilities of assured satisfactory beaching, subsequent relaunch, limited land locomotion, and broach recovery. We were able to demonstrate the first three. Anti-broach capability was to be provided by two independently controllable reciprocators, mounted outboard on the boat. We proposed to develop a large free piston engine (Figure 8) to power a landing craft up the beach and back it down back into the surf. A drawing of the free piston engines installed in the boat is shown in Figure 9. To develop this amphibious use, we mounted our concentric counter-rotating oscillator in a small Marine Corps Logistic Support Boat. The boat was 20 ft long and 7-1/2 feet wide; it weighed 1,350 lbs. The bottom is double-v shaped and the deck was flat; a substantial foam filled cavity laid between the deck and the hull bottom. We dug a small pond and lined it with plastic for testing; a beach was at one end. Figure 10 shows the boat coming out of the pond. Our third author became proficient driving that boat in and out of the pond at will. To demonstrate the beauty of the free piston engine concept, we mounted our air vibrator in a smaller boat and our third author is shown driving that boat out of the water in Figure 11. Testing in the actual surf didn't work as well, and the air cushion vehicle came along and solved the problem better than we could. We ran out of funds before we could master the technique.

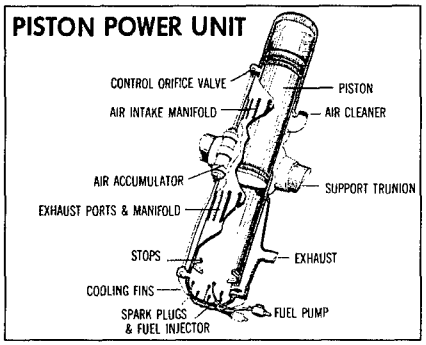

Figure 8. The free piston engine concept for use with the Beach and Launch Unit and the bulldozer thrust doubler.

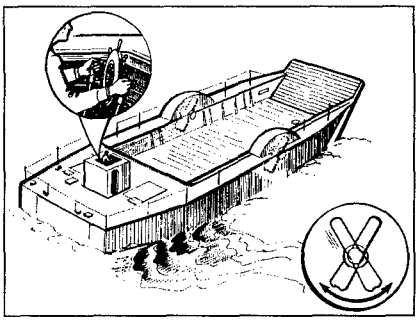

Figure 9. The vibratory locomotion free piston engines installed in a landing craft.

Figure 10. The vibratory locomotion boat emerging from the pond up onto the beach.

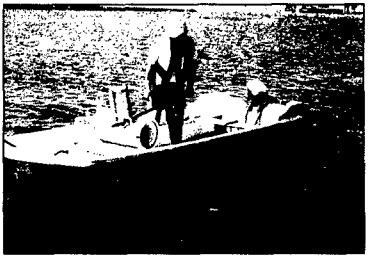

Figure 11. The compressed air vibrator installed in a small boat climbing up the beach. The long rod held by the operator is used to change the shake angle.

The final problem we attacked with our solution was doubling the drawbar of a bulldozer. A tractor can only pull with a force equal to the product of its weight and the coefficient of friction. It is easy to show that the peak pulling force of a vibratory locomotion vehicle is twice this value. Figure 12 shows what we believe to be the largest concentric counter rotating weights ever built. They could shuffle that 12,500-pound tractor through the dirt and definitely pull with a peak force twice its weight. Figure 13 shows a close up of the small weights, which were actually used to document the thrust doubling. Again, we had hoped to be able to develop the free piston oscillator for use on the Doubler in place of the dangerous counter rotating weights.

Figure 14 shows the artist's concept drawing we used to try to convince our sponsors to procede.

Figure 12. A drawbar pull test of the bulldozer with the largest set of weights.

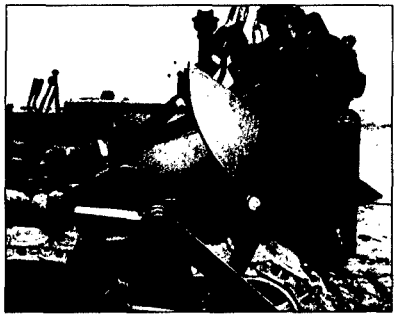

Figure 13. A close up of the small weights on the bulldozer.

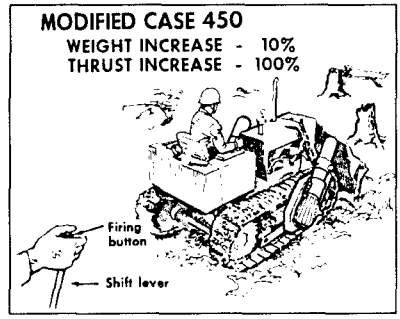

Figure 14. Concept drawing of free piston engines on a bulldozer to accomplish thrust doubling.

THE THEORY SUMMARY:

A theoretical explanation of the solution of the piece-wise linear differential equations involved in vibratory locomotion is given in Reference [2]. The solutions involved stability and had to be computed for a wide variety of non dimensional operating conditions. The results of those computations are given in a solution value map that yields the nondimensionalized step size or the net forward advance per cycle of mass oscillation for all anticipated operating conditions. Conceptually, everything but the vibrating mass is considered attached to a skid of mass m_1. The skid can slide over a terrain inclined to the horizontal amount, β, with a coefficient of friction, μ. A mass m_2 is vibrated sinusoidally with amplitude, a, and frequency ω in radians per unit time, in a straight line inclined to the skid at angle, α, as shown in Figure 15. The motion of m_2 with respect to m_1 is taken to be:

$$z = a \sin \omega t \qquad (1)$$

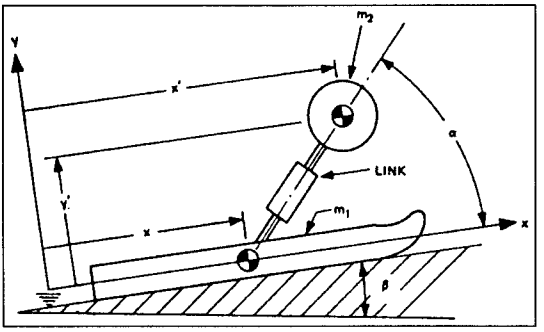

Figure 15. The theoretical model, the coordinate system and the angles.

The intensity or vibration amplitude, A, is given by:

$$A = \frac{a\omega^2 \sin\alpha}{g\cos\beta} \tag{2}$$

where, g, is the acceleration of gravity. The relative mass, M, is given by:

$$M = \frac{m_2}{m_1 + m_2} = \frac{w_2}{w_1 + w_2} \tag{3}$$

Shuffling mode vibratory locomotion takes place when the following two conditions are met:

$$MA \leq 1.0 \tag{4a}$$

$$\phi MA > 1.0 \tag{4b}$$

where:

$$\phi = \frac{\mu + \cot\alpha}{\mu + \tan\beta} \tag{5}$$

When m_2 is vibrated such that MA >1., small flights occur once per cycle so long as:

$$MA > \sqrt{\pi^2 + 1} \approx 3.297 \tag{6}$$

Beyond this limit the motion cannot be once per rev periodic.

The value of MA, if greater than one, yields three times of flight and impact [2]. It distinguishes a compactor from a vibratory locomotion vehicle. Compactors require a flight to develop an impact and thus must operate such that the flight occupies a substantial portion of the cycle; minimum values of MA are about 1.5 for compactors, with most operating close to MA= 3.0. In contrast, vibratory locomotion vehicles are not built to suffer such impacts; in fact they operate 90% of the time at values of MA less than unity. The highest drawbar pull is obtained with MA < 1. Thus devices with MA > 1 are compactors and devices with MA < 1.1 are the subject of vibratory locomotion.

To compute to the cyclic advance for any set of operating conditions from the solutions map in Reference [2] you need:

$$\psi = (\mu + \tan\beta)\sin\alpha \tag{7}$$

Then for values of MA and ϕ, the design chart gives the value of $S/(\psi M)$. From the computed values of ψ and M, calculate s, where:

$$s = aS \tag{8}$$

and "s" is the actual net displacement for each cycle of oscillation. The average velocity will be the product of the step size, s, and the frequency in cycles rather than radians per unit time, then:

$$v = sf, \tag{9}$$

SIMPLIFIED DESIGN:

If a device works on level ground, it will easily go down hill, and will climb uphill to a certain extent, so at first, we only consider level operation. You will have to fabricate a more complicated oscillator that can conveniently vary its shake angle to be able to climb uphill better. The hardware we built took such a beating when we "flew" it, that we seldom ran it that hard. Therefore, we only designed it to a maximum condition of MA = 1, which means that at the peak of the stroke, the weights are just lifting the full vehicle weight. Since this occurs for just an instant, no flight occurs. We make one further simplification for design; the theory gives a minimum shake angle for which no back slide can occur. This is probably the most efficient shake angle, for no power is wasted in backward sliding and yet the shake direction is leaning forward as much as possible to tend to the largest step possible without any back slide. Given these conditions for design (level terrain or $\beta = 0$, minimum shake angle for no back slide, MA = 1), the simplified procedes as follows. With MA = 1, and $\beta = 0$, Equation (27a) from Reference [1] gives the limiting condition for no back slide to be $\phi = 3$. Using this value and $\beta = 0$, in Equation (5), the shake angle must be:

$$\tan\alpha = \frac{1}{2\mu} \tag{10}$$

Proceeding to the design chart in Reference [2], the design parameter $S/\Psi M$, is obtained for the values $\phi = 3$, and MA = 1, to be:

$$\frac{S}{\Psi M} = 7.11 \tag{11}$$

S and Ψ are (for $\beta = 0$)

$$S = \frac{s}{a}, \text{ and} \tag{12}$$

$$\Psi = \mu \sin \alpha \tag{13}$$

where "s" is the length of a single step.

Using Equations (12), and (13) in (11) yields:

$$s = 7.11 M a \mu \sin \alpha \tag{14}$$

For MA equal unity, and $\beta = 0$, Equation (2) yields:

$$M = \frac{g}{a\omega^2 \sin \alpha} \tag{15}$$

Frequency in cycles per unit time is related to ω by $2\pi f = \omega$; using this and Equation (15) in (14) we finally obtain:

$$s = 7.11 \frac{\mu g}{(2\pi f)^2} \tag{16}$$

Taking $g = 32.17$ ft/sec^2 this becomes:

$$s = 69.53 \frac{\mu}{f^2} \tag{17}$$

where "s" is in inches and "f" is in Hz (cycles per sec.). For a surprisingly common number of situations, 0.5 is a good value to take for the coefficient of friction (e.g., timbers on sand, loose earth, wood on pavement), and for this case (10) becomes:

$$s = \frac{34.77}{f^2} \tag{18}$$

where again "s" is in inches and f is in Hertz. The velocity of the skid is the step size times the number of steps per unit time or the frequency, thus Equation (17) yields

$$v = 69.53\frac{\mu}{f}, \tag{19}$$

and Equation (18) becomes:

$$v = 34.77/f \tag{20}$$

where, once more, "v" is in inches per second and "f" in Hz. The above is a striking result; the step, size only depends on frequency. The lower the frequency the larger the step size and the velocity. Unfortunately very low frequencies cost a great deal and high frequencies are cheap.

So, the way you design is by selecting a step size, velocity and frequency from Equations (17) or (18). Using the design friction coefficient, the shake angle is selected from Equation (3), and then a trade-off between heavy weights, m_2 and a short shake amplitude, a, ensues. Sometimes the resulting oscillator size is too big for the skid to be moved, so you relax your requirement for so great a velocity, increase the frequency, and try again.

Only a few power calculations have been made, but these indicate 60 to 75% of the theoretical power to drag the skid at the design velocity. Therefore, we suggest that, since one does not want to attempt hardware with insufficient power that a good design criteria is to have the full theoretical power available to drive the weights. The theoretical power is the product of the force and the velocity; the force is the product of the coefficient of friction and the total weight, W_t, and the velocity is given by Equation (12), thus:

$$P = 69.53\frac{\mu^2 W_t}{f} \tag{21}$$

where "P" is in in-lbs/.sec, W_t in lbs, and "f" in Hz. Converting the above to the units, Hp, gives:

$$P = 0.0153\frac{\mu^2 W_t}{f} \tag{22}$$

When μ has the common value 0.5, the above becomes:

$$P = 0.002634\frac{W_t}{f} \tag{23}$$

where W_t is in lbs and "f" is in Hz, and "P" is in horsepower.

The above summarizes the simplified design. It is interesting to use the above to design an oscillator for the LCM-8. The LCM-8 is a 74 ft long landing craft that weights 250,000 lbs fully loaded; it is powered by two 325 Hp diesel engines. Assume we want it to crawl across the beach with 2.5 inch steps. Taking the friction coefficient to be 0.5, Equation (17) yields the frequency to be 3.75 Hz. With $\mu = 0.5$, Equation (10) gives the shake angle to be 45°: Equation (20) yields the velocity to be 9.27 inches per second. Equation (23), indicates that the power required to drive the weights will be about 176 Hp. The hull of the boat is about 9 ft deep with quite straight sides. Assume we might fit two sets of counter-rotating weights, one on each side, about amidships, each set having two weights as we did with the doubler. The distance, A, is the distance from the axis of the weight out to its center of gravity; this is assumed to be 40 inches in Equation (2) which yields an "A" of 40.7. The product MA must equal unity, so M = 0.0246. Substituting this value into Equation (3), with m_1 equal to 250,000 lbs one computes m_2 equal to 6,297 lbs. Since there are to be four weights, each must weigh 1,574 lbs. Such a weight with a 4-ft outside radius can easily be cut from 4-inch steel plate.

There would still be many design problems to solve. The weights would have to be synchronized because if one lifts while the other pushes down, nothing happens. The two weights synchronized would not permit any directional control. The only present conception is by varying the shake angle of one of the two sets; one could be pulling forward while the other was pulling backward. As can be imagined, such large weights have a good deal of energy stored in them when up to speed; it would take a great deal of power to bring them up to speed fast and thereby offer quick response. It is our feeling that counter-rotating weights could be developed into an acceptable system, but we are unsure. That the boat would come out of the water and walk on the sand, there is no question; the only question would be concerning the clumsiness and responsiveness of such a system. It would have to be built and tried for an accurate answer.

CONCLUSION:

To our knowledge, no one, with the exception of us, has ever built any of these. Two articles were published attempting to extend our analyses [3], [4]. The first author of this paper has copies of Reference [2] and can provide a limited number of them. The Technical Information Center at the Naval Facilities Engineering Service Center, 1100 23rd Avenue, Port Hueneme, California, 93043-4370, can provide copies of References [5] and [6]. If you consider applying the technology and have questions, the first author can be reached at hagaberson@att.net

ACKNOWLEDGEMENT:

Those marvelous drawings of our concepts for applying vibratory locomotion were drawn by Dan Nunez of Oxnard, California, an artist now retired like the rest of the authors from the Naval Civil Engineering Laboratory.

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DIAGNOSTICS

Chair: Mr. Mark L. Hollins
Naval Air Warfare Center/AD