RECENT DEVELOPMENTS IN MASS DRIVERS

Gerard K. O'Neill*
Princeton University
Princeton, New Jersey

Abstract

In the past eight months a new mass driver concept has been explored through calculation and inductance model verification. It retains the linear synchronous principle and freedom from arcs, plasmas or physical contact between the accelerated bucket and accelerator. However, it discards passive magnetic flight and obtains transverse focussing from strong off-axis restoring forces produced by drive coils operating in a pull-only mode. This paper gives the reasoning on which the new concept is based, and applies the concept to a lunar catapult design.

In order to understand clearly the reasons why our group is enthusiastic about this new development, we list here for contrast the characteristics of the earlier, "classical" mass driver concept on which we have been working for several years, and whose laboratory test program is being reported in the following paper. Figure 1 gives the energy-transfer integral for all mass-drivers, and Fig. 2 gives the schematic for an axial single-coil mass-driver.

$$\Delta E = I_B \int_{x_i}^{x_f} I_D(x) \frac{dM}{dX}(x)dx$$

Fig. 1. Energy transfer integral, giving the energy ΔE transferred to kinetic form in a single passage by a bucket coil of I_B ampere-turns through a drive coil of $I_D(x)$ ampere-turns. The coordinate x is the distance between coil planes and dM/dx is the gradient of mutual inductance.

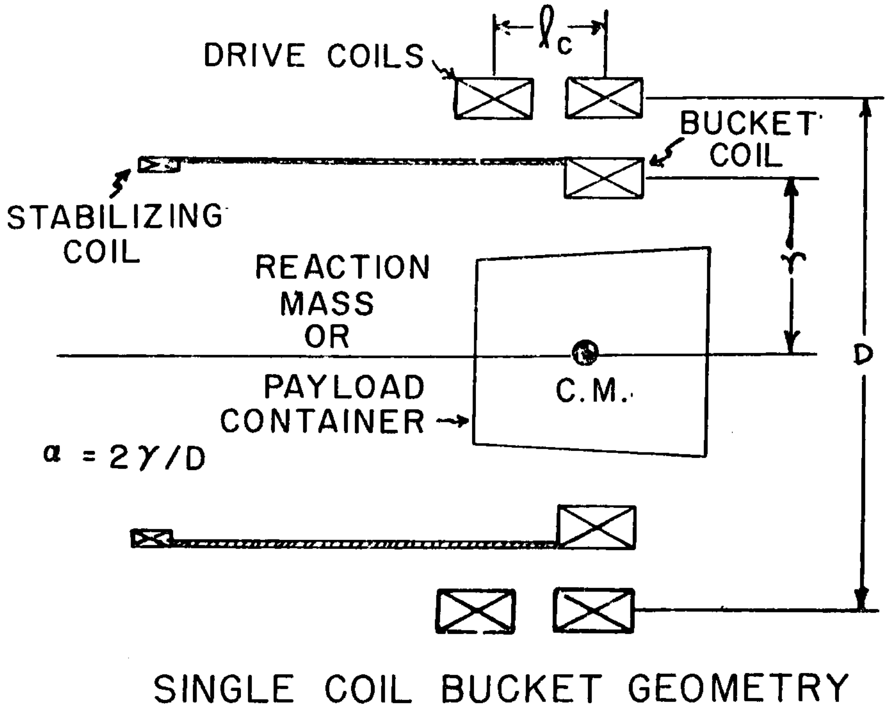

Fig. 2. Schematic diagram (not to scale) for a single-coil bucket in an axial mass-driver. Maximum drive and efficiency are obtained by concentrating nearly all the ampere-turns of the bucket into a single coil.

*Professor, Dept. of Physics, Member AIAA

In the "classical" mass driver, each drive coil resonates through a half cycle of current as the first bucket coil passes through it, and then a short time later resonates through a reverse half cycle, providing in that way a pull force as each bucket coil approaches and then a push force as the bucket coil recedes. The frequency of the current half cycles is relatively high, because the current waveform is designed to peak at the place where dM/dx, the mutual inductance gradient, is at its maximum (Fig. 3).

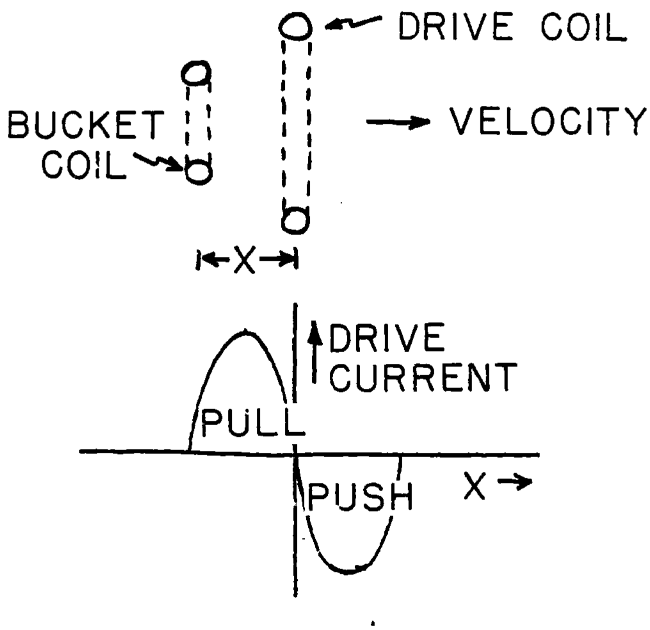

Fig. 3. "Classical" mass-driver $I_D(x)$ versus x.

For example, using the parameters of our MD-2 laboratory model, the oscillation frequency corresponding to the maximum velocity end of a lunar catapult (v = 2400 m/s) would be in the ultrasonic range at about 36 kiloherz. We have always recognized that this posed a problem for the switching SCRs (silicon controlled rectifiers) that would handle the drive coil currents, because SCRs are limited primarily by di/dt, their current rate of change, by voltage, and by recovery time before forward voltage can be reapplied to them. As coil voltage is a product of inductance and di/dt (neglecting mutual inductance and back EMF effects) the requirement of a high operating frequency doubly compounds a problem, impacting SCR limits both on di/dt and maximum voltage. It had been our assumption that the development of a satisfactory lunar launcher catapult or mass driver reaction engine would have to await advances in the solid state art.

In the "classical" mass driver there was another problem, not perceived as such because we had not imagined a better alternative. The problem was the requirement that we interpose between the drive coils and the path of the moving bucket a continuous set of longitudinal conducting guide strips, in which image-currents could be induced in order to provide the bucket with passive restoring forces in the transverse direction (i.e., "magnetic flight"). These guide strips impacted performance in two ways: as conductors, they acted as shields partially blocking the penetration of the drive magnetic fields to where those fields were needed, at the bucket coils. And as physical obstructions they forced us to make the bucket coil diameter much smaller than the drive coil diameter, in order to provide adequate physical clearance. Our test model MD-2 has a ratio alpha of only 0.51 between those two diameters. That is far from being tight coupling; put another way, it results in relatively low values of dM/dx even at the peak of that function. (Fig. 4)

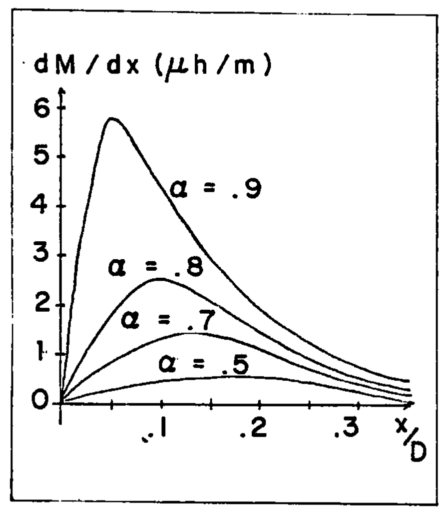

Fig. 4. Variation of dM/dx function with α, the ratio of bucket coil to drive coil diameters.

In the new concept mass driver, we preserve the essential features of all mass drivers -- control of currents by solid state or other long lived devices, freedom from physical contact between moving surfaces, and reusability of the bucket -- but we meet the requirements in radically different ways. First, we abandon the idea that the drive coil should produce a symmetrical pull-then-push to the moving bucket coil. It produced only a pull, and rests (current = 0) as the bucket coil recedes. (Fig. 5)

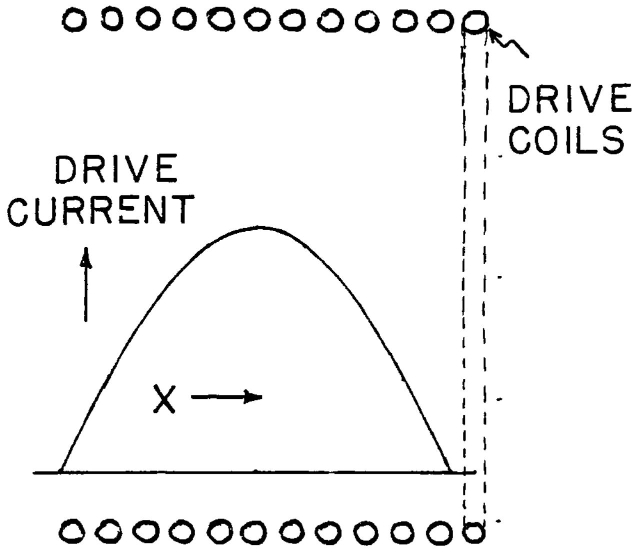

Fig. 5. Drive current $I_D(x)$ for the long-wave pull-only mass-driver.

That allows the switching SCR to have an arbitrarily long time, limited only by the number of independent drive circuits (phases) we are willing to provide, to recover before forward voltage is reapplied to it; in principle, we can therefore meet any SCR recovery time constraint no matter how high the velocity at which the mass driver is called upon to operate. Next, we abandon entirely the concept of magnetic flight, and in so doing get rid of the troublesome conducting guide strips which degrade drive field penetration and limit the tightness of coupling in the "classical" design. Instead, we obtain a restoring force in the transverse direction simply as the transverse component of the pulling magnetic drive field (Fig. 6). In the original symmetric-waveform design those restoring forces acting during the pull portion of the cycle were to first order cancelled by destabilizing transverse forces equal in magnitude and opposite in direction, acting during the push (receding bucket) portion.

Next, we go to a much greater coil diameter than used in the original concept, and having freed ourselves from the guide strips can now go to very much tighter coupling (ratio alpha of bucket coil to drive coil diameters approaching unity) while preserving as much physical clearance between moving surfaces as we had in the classical design. We run at a very much lower frequency, so the useful region in which each drive coil pulls now extends through a much longer time, during which the bucket coil passes through a large number of drive coils. Our choice of drive frequency is in fact now decoupled from the

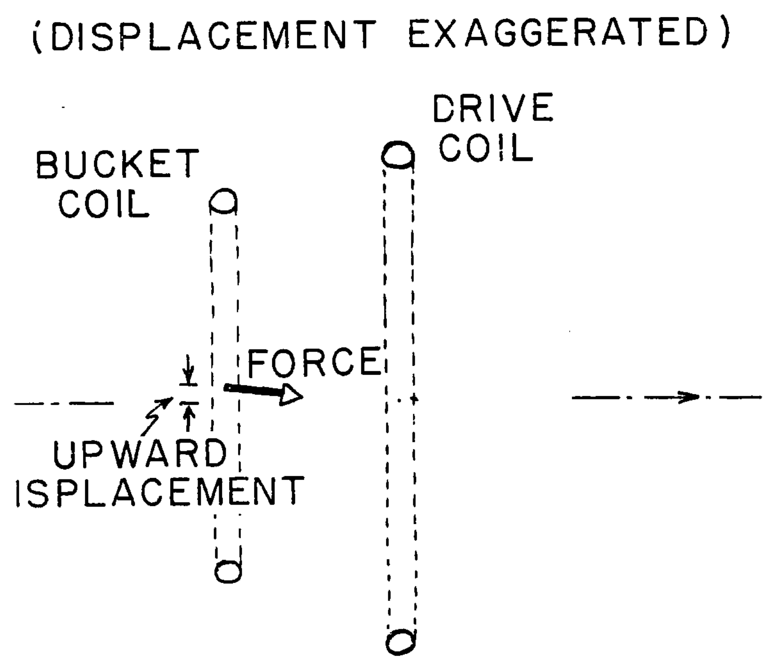

Fig. 6. Transverse restoring force in the pull-only mass-driver.

spacing between drive coils, and in principle we can now hold SCR di/dt and voltage as low as we like, no matter how high the velocity we are called upon to accelerate the bucket to.

With these radical changes, a given acceleration can be obtained at a far lower drive current, and as power goes as i^2R, the drive efficiency can be extremely high, in some cases as much as 90% or more. From a practical viewpoint, the even more significant breakthrough is that we can now plan on using SCRs that already exist as commercial off-the-shelf items, and we can plan on operating them within their catalog specifications on voltage, di/dt and recovery time. As for power limitations, our operating conditions are a factor of 1000 below handbook ratings on SCR single pulse chip heating.

To summarize, in this new concept, which we call the long-wave pull-only mass driver, the drive coil diameter is typically about 40 cm (16 inches), and the operating frequency is in the mid-audio range at around 4800 Hertz. The ratio α (alpha) of bucket coil to drive coil diameters can be high, of order 0.9, so coupling is tight and both efficiency and acceleration can be much higher than in earlier concepts. In this long-wave, pull-only mass driver many drive coils, typically 10 or more, act together. Every drive coil goes through the same current waveform, approximately a half sine-wave, the phase intervals between adjacent coils all being equal. A long-period wave therefore proceeds down the accelerator, with the bucket always located at the trailing end of the wave. Transverse focussing in the long-wave pull-only mass driver will be reported on later in this session by Steve Leete.

It has been a rather severe challenge to calculate the exact current waveform for the drive coil current in the new-concept mass driver. Typically 10 drive coils are active at one time (Figs. 7 and 8).

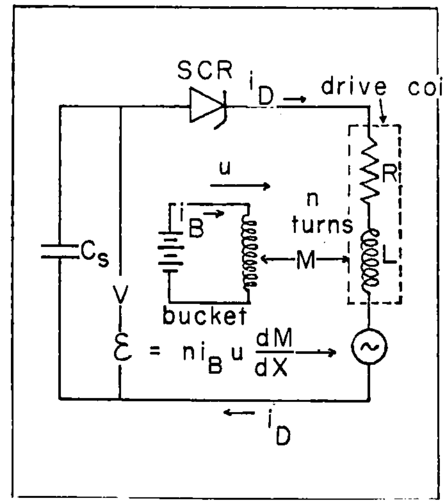

Fig. 7. Basic drive circuit for one drive coil of isolated inductance n^2L, interacting with a bucket coil carrying i_B ampere-turns. In the pull-only design a given drive coil is fed by a monodirectional current pulse, requiring only one switching element (SCR or equivalent).

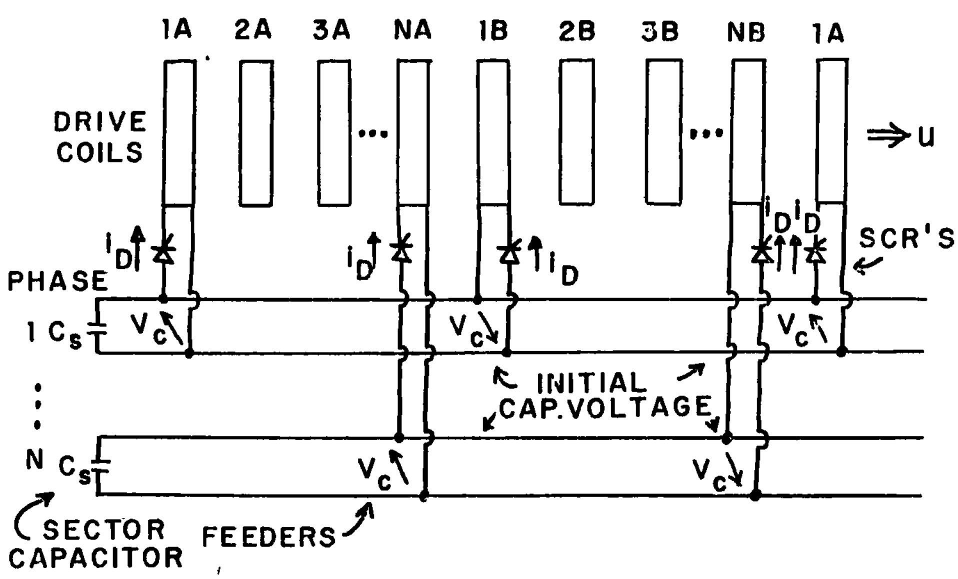

Fig. 8. Schematic for pull-only mass-driver having n independent circuits (phases). The number n is chosen to satisfy requirement for SCR reversed-voltage time (recovery time) before forward voltage is reapplied.

Even without considering the effects on those currents of the 10 induced EMFs from bucket motion, the system consists of 10 different circuits, all interacting through their mutual inductances. Moreover, the currents must satisfy a set of 10 recursion relations which describe the physical reality that each successive current history must reproduce what happened in coils that fired earlier, and that the history, as other coils fire and therefore become active with their mutual inductances, must satisfy the charge and voltage time relationships that exist for 10 drive circuit capacitors. We have solved the problem by coding the physics into a computer program and allowing the computer to perform successive approximations until all the recursion relations and all the capacitor charging integrals are satisfied for the real case of drive coil SCRs fired at equal intervals. Our final computer code converges very rapidly, giving within one or two minutes an answer accurate to many decimal places. The result for the unloaded system, shown in Fig. 9, is that the current waveform rises more rapidly than would an equivalent sinewave, and that the voltage which the SCRs must stand off is only moderately higher, by about 30%, than that of an isolated single coil given the same initial di/dt. The pull-only long-wave design is fail-safe in the sense that if any drive coil circuit fails to fire when triggered, the resulting voltage history on all neighboring drive circuit SCRs is lowered rather than raised.

Table 1 gives the approximate parameters for the high velocity end of a long-wave mass driver intended as a lunar launcher (catapult). It is based on the computer solution for 10 active drive coils, corresponding to a moving wave whose wavelength is 20 coil spacings.

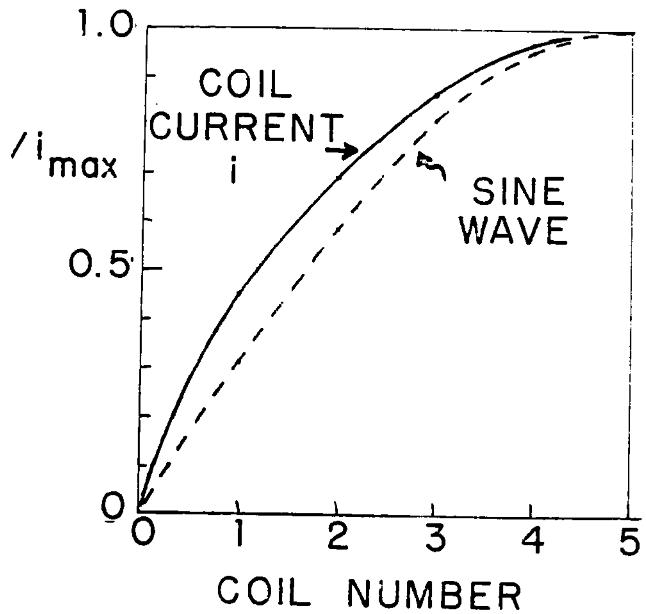

Fig. 9. Current waveform for a long-wave pull-only mass-driver in which 10 drive coils are simultaneously active. The waveform is symmetrical about coil #5, reaching zero at coil #10.

Table 1. Geometric and Electrical Parameters for a Long-Wave Pull Only Mass Driver Designed for 2400 meters/sec. (Approximate, for unloaded case.)

Maximum Drive Coil Current Derivative:	1,000	amperes / microsec
Peak drive coil voltage	1,300	volts
Peak volts/voltage for isolated coil	1.31	
Peak drive current	23,000	amps
Initial charge on capacitor	0.84	coulomb
Capacitance	660	microfarad
Stored energy in capacitor	540	joules
Drive frequency	4,800	Hz
Coil diameter	40	cm
Alpha (α)	0.9	
Drive coil spacing (centers)	2.5	cm
Number of drive-coil turns	1	

Loading by energy transfer to the moving bucket should be held to a fraction of the initial capacitive stored energy of a drive coil circuit. The effect of the induced back EMF is to reduce the forward voltage which the SCR is required to stand off just before firing; then to retard slightly the buildup of coil current and hasten the turnoff of the current cycle; and finally, as the bucket recedes, to reduce the back voltage across the SCR. Table 2 gives the performance parameters for a lunar catapult based on the design of Table 1, with loading held to 33%.

Table 2. Performance Parameters for Lunar Catapult

Bucket mass, empty	200 grams
Payload mass	200 grams
Bucket current i_B	18,500 amp-turns
Energy Transfer per drive coil	176 joules
Maximum back EMF	250 volts
Acceleration	1800 gravities
Acceleration length	164 meters
Deceleration length	82 meters
Added lengths (10% spares + peeloff)	75 meters
Total mass-driver length	321 meters
End-to-end transfer time	0.245 sec.
Payload transfer rate, frequency 4hz, 33% duty	8,400 tons/year
Drive Efficiency*	92%

*Defined as

$$\frac{\text{(Payload Kinetic Power)}}{\text{(Payload kinetic power) + (Drive coil losses)}}$$

Losses in feeders, capacitors, power conditioning and bucket handling are subjects for later optimization.

The choice of drive circuit operating impedance can be made among several alternatives, as listed in Table 3.

At the present time commercial SCRs are available within the limits of approximately 1000 amps/μs in di/dt and 3,000 volts in forward voltage. A choice of n=3 from Table 3 would therefore correspond to a series stack of two SCRs.

For the lunar catapult described in Tables 1-3, the total drive-coil mass is 15 tons. Power (2.5 megawatts) would require a solar-cell array of 35 tons, at 14 tons/megawatt. Total system mass, not yet optimized, is therefore likely to fall in the range 75 to 125 tons, for a throughput in the order of 100 tons per year, per ton of system mass.

As the design is within SCR limits and the machine can be provided with redundant sections, normally unpowered, the nominal lifetime goal is in excess of 4×10^8 shots, corresponding to four firings per second for ten years, at a 33% duty cycle appropriate to a solar-cell power source on the lunar surface.

In practice, if the lunar mass driver were operated remotely, without a continuing human presence on the Moon, there could be maintenance visits at intervals of months or years, to replace mass driver sections in which there were failed components. As long as such replacements were complete sections several meters long, it is also possible that the replacements could be carried out remotely, by manipulators riding a crane rail the length of the machine.

In Table 2 the end-to-end travel time of 0.25 second is of special significance because of a conclusion of recent months: our colleagues at M.I.T. find that the heat transfer problems involved in cooling the superconducting bucket and preserving it from reheating are fairly severe, so they have asked us to look for alternatives to superconducting bucket coils. It is well known that for times of about 0.5 second or less a current density as high as that of a superconducting coil can be maintained in an ohmic coil. We have therefore looked into ways of supplying an ohmic coil with continuous current during the 0.25 second of the end-to-end travel time, without introducing arcs or contacts. We conclude that it should be possible to supply the necessary energy by the rectification on-board the bucket of a small fraction of the ripple flux from drive coil fields as the bucket moves through the machine. In our present concept, the bucket coils are therefore simple aluminum rather than superconductor.

Experimental testing (not reported here) to check some of the concepts reported in this paper was carried out by S. Dunbar, H. Fockler, J. Kubby, S. Leete and W. Snow. It is a pleasure to thank them for their contributions.

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Table 3. Alternative Operating Conditions for Lunar Catapult

Number of Drive-Coil Turns n	Peak Drive Current (amperes)	Peak di/dt (amperes/μsec)	Charging Voltage	Sector Capacitor (μf)
1	23,000	1,000	1,300	660
2	11,500	500	2,600	165
3	7,700	330	3,900	73