OVERVIEW AND OUTLINE OF MASS-DRIVER TWO

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Abstract

An overview of the Princeton-M.I.T. second mass-driver is presented. Mass-Driver Two is a 13.1 cm caliber system which uses a two coil superconducting bucket and a two-phase in quadrature drive system. Discrete drive coils are individually energized with timing supplied by position-sensing optical detectors. Intermediate energy storage is provided by sector capacitors which are recharged every half cycle by an external power source. A vacuum environment is provided for the superconducting bucket by a 4 inch i.d. glass pipe with the drive coils surrounding it. Magnetic flight is generated by eddy current repulsion from six copper guide strips lining the glass pipe. The length is 2.5 meters equally divided between acceleration and deceleration sections. Nominal acceleration is 5000 m/s^2 giving a maximum bucket velocity of 112 m/s. Regenerative braking is used to decelerate the bucket. Current densities of 25 KA/cm^2 are achieved in the superconducting bucket coils and are maintained by a cryogenic service station. Studies of guidance forces, acceleration forces, measurement of drive shielding losses, and possible coupling of acceleration forces into modes of transverse and rotational oscillation of the bucket will be performed.

Introduction

The essential elements of a mass-driver linear motor are acceleration by mutual inductance gradient dM/dx, control of drive-circuit timing by position-sensing, magnetic flight, intermediate energy storage by sector capacitors, separation of load and armature (bucket), and recirculation of the bucket. These essentials, and incidentally, the term "mass-driver itself", were first combined five years ago, and were described at the first Princeton Conference in 1974.[1] Little more work was done on the mass-driver concept until 1976. Then, in the 1976 NASA-Ames Study and in the intensive year of cooperative Princeton-M.I.T. work that followed, the mass-driver concept reached maturity.[2,3] Mass-optimization formulae were obtained, H.H. Kolm's more efficient axial geometry was adopted, and a convenient method was developed for the accurate calculation of acceleration. The mass-driver group at the 1977 NASA-Ames study concentrated therefore on detail refinement and simplification of the basic design, and on longer-term questions such as mechanical stability of the linear structure, a survey of commercially available components, and optimization of exhaust velocity as a function of mission velocity-interval (Δv).[4-6] During that study the electrical design was simplified and efficiency was increased by adoption of a two-coil bucket geometry, a two-phase, quadrature drive system, and bridging between sector capacitor banks. In the nearly two years since then the electrical design has remained essentially unchanged, and perhaps can be regarded as "asymptotic" until or unless someone offers a major new insight.

By the Autumn of 1976 our understanding had progressed to the point where a first model was appropriate; "Mass-Driver One" was then built in the early months of 1977, and demonstrated at the May 1977 Princeton/AIAA Conference.[7,8] Successful as it was, we should recognize that it was simple and primitive. It lacked magnetic flight, used an ohmic rather than a superconducting bucket, and employed a very simple monophase, half-wave drive system with one capacitor per drive coil, triggered by mechanical switches.

Mass-Driver Two: Basic Configuration

By mid 1977 it became clear that the next step in development should be primarily the experimental verification of theory rather than its further elaboration. One of us (W.S.) came to Princeton at that time with support from the Space Studies Institute.

A division of responsibility was agreed on between the Universities involved: M.I.T. would concentrate on the superconducting bucket, all aspects of its cryogenic service station, and guidance measurements, while Princeton would concentrate on the accelerator. All parameters of Mass-Driver Two affecting the interface between bucket and accelerator were settled in joint design meetings during the Autumn of 1977, and support by the NASA Space Propulsion and Power Division resumed at the end of that year. The first half of 1978 was devoted to detail design and the search for components. Mass-Driver Two combines for the first time all the essential elements of an operational mass-driver with the exception of bucket recirculation and payload handling. These essential elements include: a)magnetic flight, b)vacuum environment, c)superconducting bucket coils, d)high acceleration (several hundred g's), e)optical triggering, f) power circuitry similar to that of a flight article, and g)regenerative braking. Mass-Driver Two operates on a single-shot basis.

A lucky windfall occurred in 1978: a large quantity of components, including especially high-voltage high-current silicon-controlled-rectifiers (SCR's) and capacitors, became available on surplus lists. These items, formerly parts of the Princeton-Pennsylvania 3GeV Proton Synchrotron, are the property of Princeton University and were made available to us through the courtesy of Prof. Milton G. White, Director of that project. The total value of that

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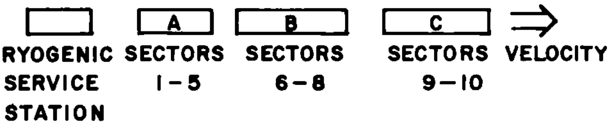
**Research Assistant, Department of Physics, Member AIAA equipment considerably exceeds the NASA and SSI funds available to us in 1978 and 1979.

The components now on hand will permit the assembly over several years of nearly 20 meters of accelerator; at nominal acceleration the mid-point velocity (in vacuum) should then approximately equal the speed of sound in air. Resources permitting, the accelerator could continue to grow in length and velocity far beyond that point.

We have planned for three stages of development in our detailed design (Table 1):

Table 1 Mass-driver nominal performance and terminology

Name	Total length, m	Nominal peak velocity, m/s	mph
Mass-Driver Two	2.5	112	250
Mass-Driver Three	10	224	500
Mass-Driver Four	18	300	670



SECTOR	#COILS	#END COILS	SECTION TOTAL
1-3	19	4	—
4	14	0	—
5	18	4	59
6	22	4	—
7	26	0	—
8	30	4	86
9	35	4	—
10	39	4	82
1-10	—	—	227

CONFIGURATION OF MASS-DRIVER TWO AND THREE ACCELERATION SECTIONS.

FIG. I

Each model will be developed from the previous one by the addition of higher-velocity acceleration and deceleration sections between the pre-existing lower-speed sections, which will be moved apart to accommodate them. In most respects the earliest stage, Mass-Driver Two, is the most difficult to design and build: it must include the transition of the bucket from rest to and from a speed adequate for magnetic flight, and accommodation to a velocity varying rapidly over the distance of only a few drive coils. The nominal parameters of Mass-Driver two and Three are given in Table 2; in English units the drive coil diameter is about five inches, the spacing of drive coils about one inch, and the bucket coil diameter is about half that of the drive coils. For a bucket mass of 2.2 lbs. (1 Kg) nominal acceleration is 500 gravities, in contrast to Mass Driver One's 33 gravities. Because of the speeds to be expected in Mass-Driver Three and Four, and to provide vacuum insulation for the cryogenic bucket, the accelerator and bucket are separated by a glass vacuum-pipe. The inner wall of the pipe is lined with copper strips to form a magnetic-flight guideway. The bucket coil spacing is eight drive-coil spacings, and the bucket coil currents are in the same sense; that will simplify the future addition of active steering by magnetic quadrupoles in a long accelerator. The physical dimensions and drive coil inventory for Mass-Driver Two and Three

Table 2 Nominal parameters for mass-driver two and three[a]

Sector	Position, m	Velocity, m/s	Ringing frequency, rad/s	Hz	Ringing period, μs
1	0.05	22.4	1428	227	4400
2	0.20	44.7	2856	455	2200
3	0.45	67.1	4283	682	1467
4	0.80	89.4	5711	909	1100
5	1.25	111.8	7139	1136	880
6	1.80	134.2	8567	1363	733
7	2.45	156.5	9994	1591	629
8	3.20	178.9	11,420	1818	550
9	4.05	201.3	12,850	2045	489
10	5.00	223.6	14,280	2273	440

[a] With caliber $D= 13.06$ cm; bucket/drive coil diameter ratio $\alpha= 0.514$; acceleration $a= 5000$ m/s; drive coil spacing $\ell_m= 2.46$ cm; and injection velocity from the cryogenic service station $u_0= 0$ m/s.

are shown in Fig. 1. Mass-Driver Two consists of the cryogenic service station plus acceleration and deceleration sections A (Sectors 1-5), with 59 drive coils in each.

Accelerator Design

The two-phase in quadrature drive system is energized in groups of four drive coils per phase resonating with a sector capacitor bank. These controlled pulsed electromagnetic fields provide the drive force required to accelerate the superconducting bucket, which possesses its own constant magnetic field. In Mass-Driver Two sectors 1-5 of each phase resonate with a common sector capacitor bank rather than individual capacitors for each sector. Figure 2 shows a representative segment of the drive circuit for one phase. Stripline is used extensively to minimize lead inductances.

At the high-speed end of Mass-Driver Two the parameters relevant to the SCR's are given in Table 3. For 500g acceleration and an assumed 20% loss of drive, mainly due to field-shielding by the guideway, the SCR's must stand off 670 volts and switch 6300 amps. The parameter di/dt is significant in preventing excessive temperature rise at a "hot spot" occurring on localized regions over the silicon chip during turn-on switching. The parameter i^2t determines the total input of heat to the chip during its short pulse, and must be limited to avoid thermal shock.

Table 3 Main parameters in higher speed sectors (at their midpoints) of mass-driver two

Parameter	Sector 4	Sector 5	Units
Ringing frequency	6.8	9.3	10^3 rad/s
Capacitor bank	2100	2040	μf
Capacitor voltage	641	668	volts
Number of turns	8	6	
Peak current	4610	6315	amps
di/dt	31.6	58.6	amps/μs
dV/dt	4.4	6.1	volts/μs
i^2t	19,500	27,000	amp^2sec
Firing offset	6.7	7.6	mm
Recharge time	170	150	μs

The logic circuits that set the order and timing of drive coil firings (each coil must be supplied with four independent half-cycles of current

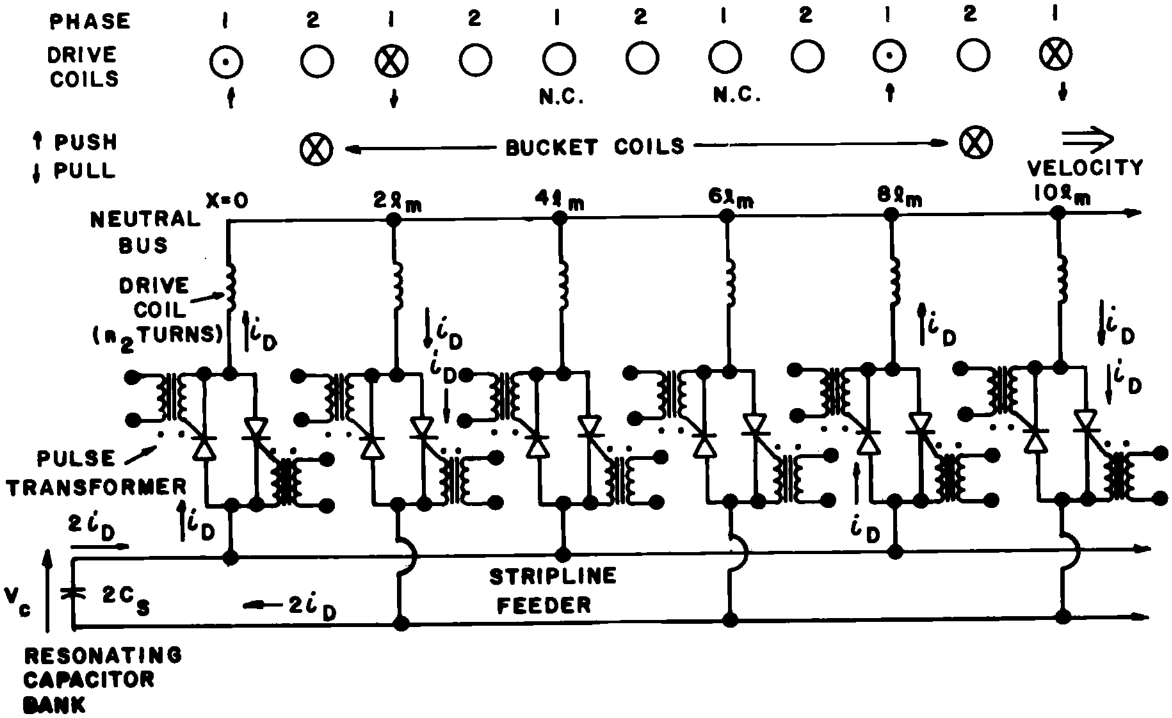


Fig. 2 Six drive coils of phase 1, shown at the time of peak positive current; at this time there is zero current in phase 2. Four coils are excited, one to pull and one to push each of the two bucket coils. Spacing ℓ_m is chosen equal to the separation between a drive and bucket coil at peak gradient dM/dx. SCR's are triggered through pulse transformers for electrical isolation between the drive circuit and the electronic triggering circuitry.

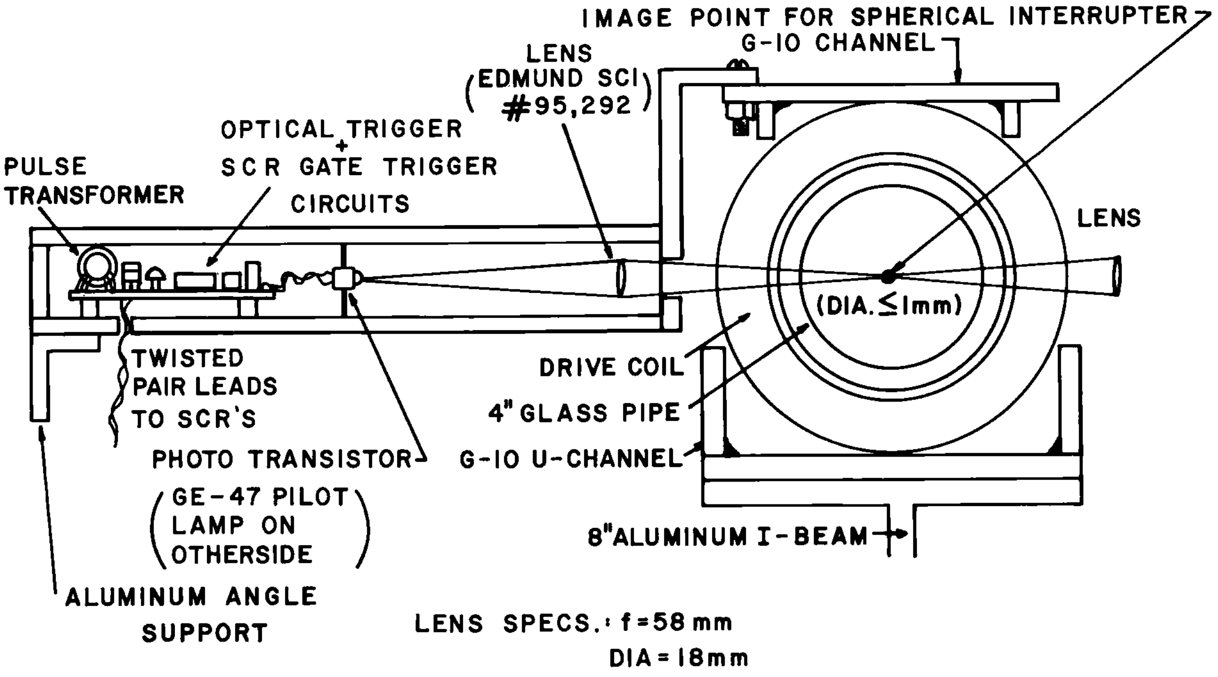
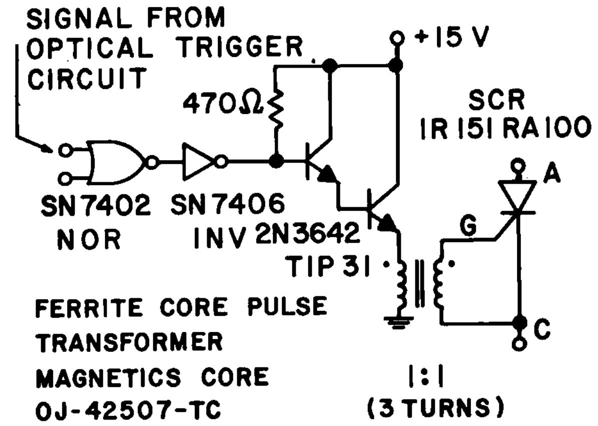


Fig. 3 Normally-on light beam focused to a real image at center of guideway is refocused onto photo transistor. Light beam is cut by spherical interrupter centered on center-of-mass of bucket (to make the timing insensitive to bucket pitch and yaw).



SCR GATE TRIGGER CIRCUIT
FIG.4

oscillation, two of each sign) receive their timing signals from optical triggers (Fig. 3) located before each drive coil. One output of the logic circuits feeds a current amplifier (Fig. 4) that triggers a particular SCR through a ferrite-core pulse transformer. All low-level circuitry up through the pulse transformer is within a shielded enclosure.

A high-current, high-speed full-wave recharge circuit must restore each sector capacitor to full voltage during brief (typically 100-150 μs) periods between half-cycles of drive-coil oscillation. For that reason the oscillation period is chosen to be approximately two-thirds of 4 ℓ_m/u, where u is the bucket velocity (Fig. 5). Design of the recharge circuit was a major task of early 1979, and we are indebted to the NASA-Lewis Research Center for technical advice and documents that were most helpful for that design.

A non-cryogenic ohmic bucket (Fig. 6) was designed in order to permit convenient testing of the accelerator without the need for vacuum or liquid helium. The ohmic bucket can sustain a current adequate for 500g for more than 0.2 sec., without heating by more than 40°C from an initial temperature of -200°C (liquid nitrogen temperature). For comparison, the transfer time (end to end) for Mass-Driver Four (eighteen meters) will be nominally 0.12 sec.

Construction

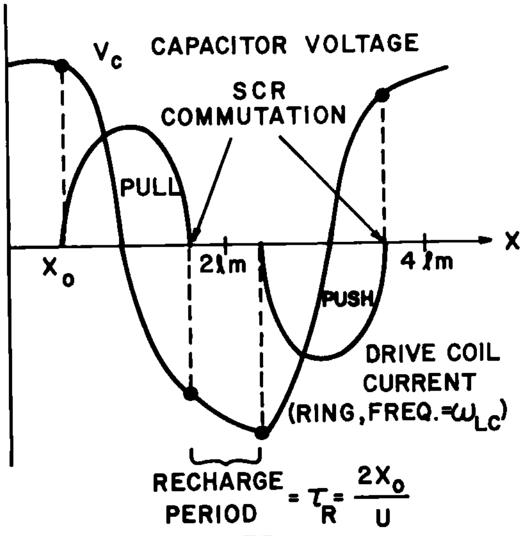
Most of the drive coil winding and other mass production of components for Mass-Driver Two and Three was completed during an intensive period of work by (David Kaplan, Rainer Malzbender, Linda Plano, and Robert Zacher) student assistants during the Summer of 1978. Much work was also done by student volunteers: J. Lawrence Buell IV, Janice Enagonio, Neil Gershenfeld, Stephen Leete, Jonathan Newman, William Niedringhaus, and Mark Psiaki.

At the end of 1978 NASA substantially increased its support of the mass-driver work, and we added to the group W. Werosta, an experienced machinist, to build precision hardware needed especially for the optical system. L. Hagopian also joined the group half-time early in 1979. The design and construction of the cryogenic service station, superconducting bucket, and accelerator for Mass-Driver Two are described in the companion papers.[9,10] Complementary work done by student volunteers in the course of Junior Papers or Senior Theses will be reported in other papers.

Concluding Remarks

Mass-Driver Two cannot be brought to the site of this Conference, because of floor-loading limits. These would be reached by the oversized, very heavy surplus capacitors used in the sector banks and recharge system. Mass-Driver Two is located in Room 361 of Jadwin Physics Laboratory.

Once routine operation of Mass-Driver Two is reached we plan an extensive program of testing in cooperation with our M.I.T. colleagues. We



RECHARGE PERIOD $= \tau_R = \frac{2X_0}{U}$

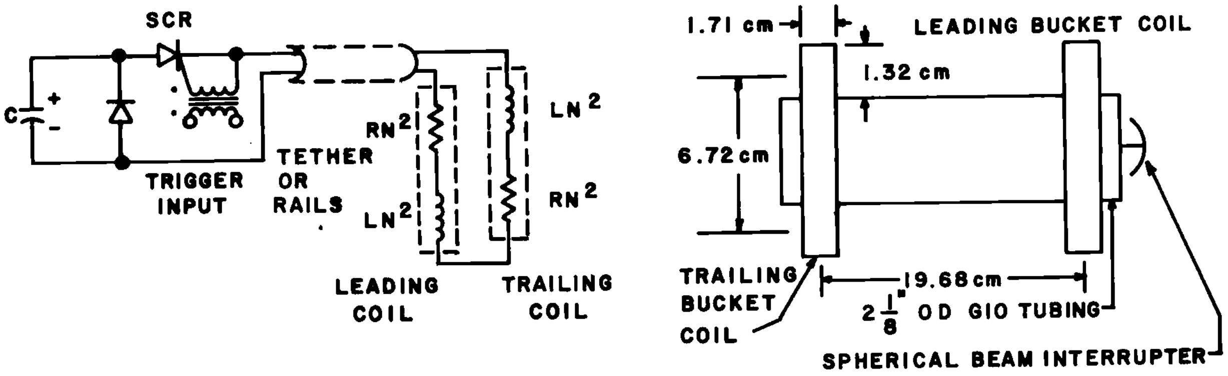
X_0 = FIRING OFFSET

$$X_0 = \frac{1}{4}\left(\frac{4\ell m}{U} - \frac{2\pi}{\omega_{LC}}\right)$$

U = LOCAL BUCKET VELOCITY

CURRENT WAVEFORM IN ONE DRIVE COIL DURING TRANSIT BY ONE BUCKET COIL

FIG.5



CIRCUIT DIAGRAM

CROSS SECTION VIEW

SPECIFICATION

CURRENT DENSITY	7375 amp/cm^2	INPUT ENERGY	141 Joules
ON TIME	0.1 sec	CONDUCTING AREA	1.72 cm^2
T INITAL	-200 °C (LN$_2$ cooled)	CROSS SECTION AREA	2.26 cm^2
T FINAL	-189 °C	CONDUCTING MASS	107 cm^2

OHMIC BUCKET DESIGN

FIG. 6

anticipate studies particularly of guidance forces, comparison of drive acceleration with theory, measurement of drive shielding losses, and possible coupling of acceleration forces into modes of transverse and rotational oscillation of the bucket. Mass-Driver Two is a research device, a "test bed" which we expect to modify and rebuild as necessary.

Acknowledgement

For support during the design and construction of Mass-Driver Two it is a pleasure to thank the Space Studies Institute, NASA Headquarters Electric Propulsion Systems Branch, and the Power Devices Section of the NASA Lewis Research Center. This work was supported in part by the National Aeronautics and Space Administration under Grant NSG 3176.

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(Though not relevant to mass-driver design nor to this paper, there is a minor error in the second of the two papers of Vol. 57 (ref. 3, p.79), kindly called to our attention by T.A. Heppenheimer. Payload charging prior to electrostatic guidance must be accomplished by an electron beam. With that change, all the results of the reference paper are as published.)

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Q. Was there any attempt to use materials that would be available from lunar sources?

A. There was no such attempt. For example, just for simplicity (and because we could get surplus materials) the drive coils are wound out of copper, whereas they would be aluminum in the real case. In fact, most of the parts are surplus.

Q. Did you do any calculations on cost per unit length? What is the cost of the present mass driver components?

A. No, all the parts we are using were obtained surplus. We didn't have to pay for them. However, there have been fairly detailed cost studies carried out.

Q. Is the capacitor ringing frequency being varied?

A. Yes. The frequency changes about every inch or two that the bucket moves along. That's why the sectors are very short in the beginning and then progressively get longer. In the high speed region it is possible to tolerate the order of a 10% speed variation relative to the capacitor ringing frequency. Near the beginning the sectors almost have to be trimmed coil by coil.

Q. Does the capacitor bank resonate with each individual coil?

A. Not quite. There are four coils energized at any given moment in a given phase, and those are being resonated with the capacitor which is hung on the sector feeder. In the downstream sectors the size of the sector capacitor is changed from sector to sector so that the frequencies stay right. The most difficult problem of all, the one we have to solve first, is going from rest to a state of motion. That's the hardest part of the mass driver to build.

Q. Is it a better design choice to use active feedback in magnetic control of bucket steering as it moves along, or is it better to use a passive, essentially dashpot type of damping system?

A. The tentative choice is to use an active system because (1) it allows the mass driver bucket itself to be of minimum mass and to have no moving parts, and (2) with a passive damping system it's the essential properties that give rise to the damping, and there is a basic limitation at the optimum, which amounts to the equivalent of critical damping. That's a physical limit, whereas with electronic feedback we can obtain whatever amplification we choose and the corrections then can be very large even for small departures from the correct position.