The ATI Programmable Steering Machine

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INTRODUCTION

The ATI Programmable Steering Machine is an easily-installed, battery-powered, "series servo second steering wheel". The steering machine is designed to execute any 16384-step steering program with force and velocity capabilities significantly greater than those of the human driver. Its EPROM memory contains sixteen separate programs, which can be programmed to duplicate any steering input with fidelity and repeatability. During the execution of a program, the handwheel is mechanically "grounded" to eliminate driver interference with measurement of steering angles and torques. The program also outputs auxiliary signals that can be used to control vehicle throttle and brakes, data recorders, or other devices.

This report describes the steering machine's design and operation, its measured capabilities, and some of the SAE, ISO, and rollover test protocols for which it is designed.

USES

Accurate measurement of a vehicle's control response requires precise, repeatable inputs from steering; and to a somewhat lesser extent from throttle and brakes. For this reason most standard ISO and SAE test protocols call for rapidly turning the steering wheel against a fixed stop and holding it there for the duration of the test. The stops must be disconnected for maneuvering before and after each test, and must be mechanically reset or readjusted for each new condition. For large steer inputs in which loss of control is possible the stop must automatically disconnect, or the driver must be able to overpower it.

Some test protocols, such as the ISO 7401 Single Cycle Sinusoid Input test [1], the 7401 Continuous Sinusoidal Input test [1,2], and the weave test for the proposed On-Center Handling protocol [3,4], require sine wave inputs which can only be approximated with manual steer input.

Dynamic rollover testing is worthless without accurately repeatable steer inputs, because one can never know whether response differences were due to changes in steer input or tires.

The general-purpose steering machine described herein was designed to make some control response tests more efficient and others more accurate. The adjustable mechanical stops used in step-input or constant steer angle tests are replaced by electronic stops adjusted by digital switches. Any arbitrary steer input can be programmed with a personal computer and a EPROM burner, from mathematical functions or from recorded data. Any of sixteen different programs can be selected by a thumbwheel switch, with direction of first turn and steer amplitude selected by two additional thumbwheel switches.

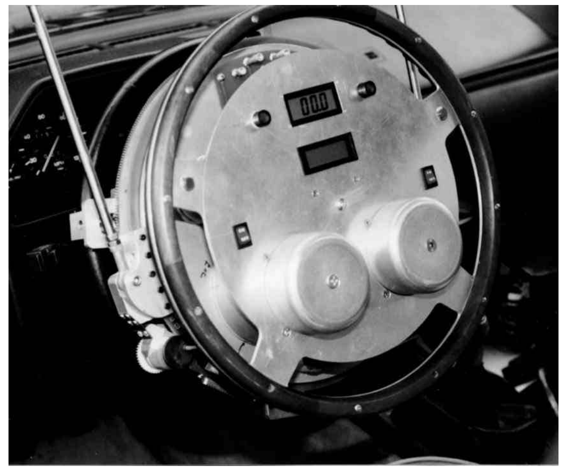

Figure 1: Machine installed in a test vehicle

This description is organized into seven parts: overall mechanization; operation; servo design; measured performance; description of a simplified "Weave Wheel"; companion devices; and use in some standard test protocols.

PART 1: OVERALL MECHANIZATION

SYSTEM COMPONENTS - The complete steering machine system consists of four components: the machine itself, the command module, the battery box, and the electronics box.

The machine is shown installed in a test vehicle in Figure 1. A cable connects the machine to an electronics box (Figure 2) which contains signal conditioning, programming, and servo amplifier electronics. The electronics box connects in turn to a hand-held "command module" and to a battery/relay assembly. The command module (Figure 3) contains three digital switches: hexadecimal program select; steering amplitude; and direction of first turn. Steering amplitude can be set in one degree increments to ±999 degrees. The battery box (Figure 4) has five 12-volt batteries of either 2.5 or 5 amp-hour capacity, which are connected in series for servo operation and in parallel with the vehicle's charging system whenever the servo is not activated.

Figure 2: Electronics box

Servo feedback from the driven plate is from a motor-mounted shaft encoder. A second shaft encoder measures the angle between the output plate and the grounding plate; i.e., the vehicle steering wheel angle.

MECHANICAL CONFIGURATION - The steering machine consists of four concentric disks or plates: the handwheel disk; the motor assembly "sandwich" plate; the grounding disk (inside the sandwich); and the driven plate. The assembly is fastened to the vehicle steering wheel by synchronous "skate key" clamps, and the grounding disk is attached to the vehicle windshield by adjustable struts fitted with suction cups.

The handwheel assembly contains two on/off paddle switches which enable/disable the ENERGIZE function and the GROUND function. The right-hand ENERGIZE pushbutton switch activates the servo amplifier and, after a self-check, releases the fail-safe brake and enables the left-hand PROGRAM pushbutton switch. This switch activates the grounding brakes and starts the program. The two panel meters are used to provide an unobstructed driver view of vehicle speed and either yaw rate or some other selected variable. The two "klutzlight" indicator lamps indicate the direction selected for the initial turn, to drivers with poor short-term memories.

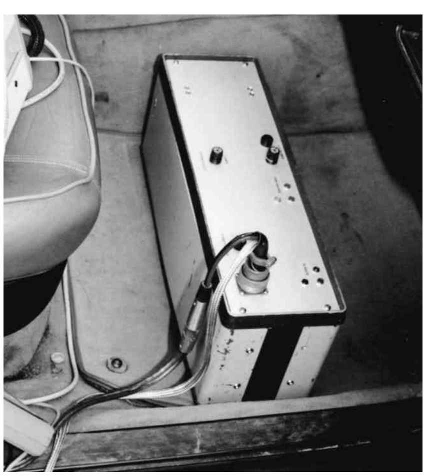

Figure 4: Battery box

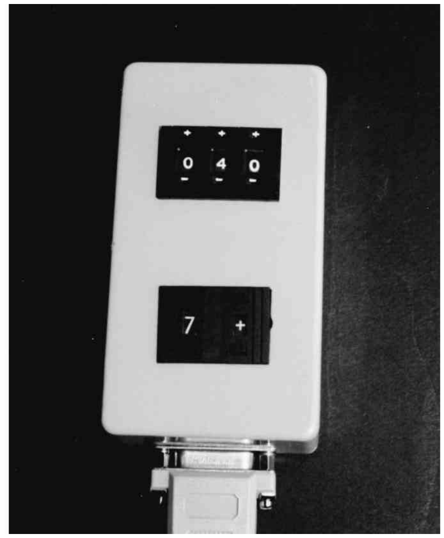

Figure 3: Hand-held Command Module

The driver's handwheel disk mechanically attaches to the servomotor bodies, and electrically plugs into a mating connector on the motor assembly plate. The domelike aluminum shells cover the spring-applied, solenoid released failsafe brake and the motor position encoder.

Figure 5 shows the steering machine with the handwheel disk removed. The upper half of the motor assembly sandwich contains the two servomotors, two grounding brake solenoids (two sizes are being evaluated in the prototype machine), and an electronics card. The electronics card contains brake relays, a DC-DC converter to isolate signal power from 12 volt power, two brush pairs for topside slip rings, and a connector from the eight bottom side slip ring brushes.

Removal of the upper half of the motor assembly sandwich reveals the grounding disk/slip ring assembly (Figure 6). This disk is made up of two double-sided printed circuits bonded together and connected to a single 37-pin connector. After bonding, the rings are plated with additional copper to increase their thickness; then with a layer of nickel for toughness and a layer of hard gold for corrosion resistance. Each ring is proportioned to the current it must carry, except the inner rings. The inner rings carry 12 volt

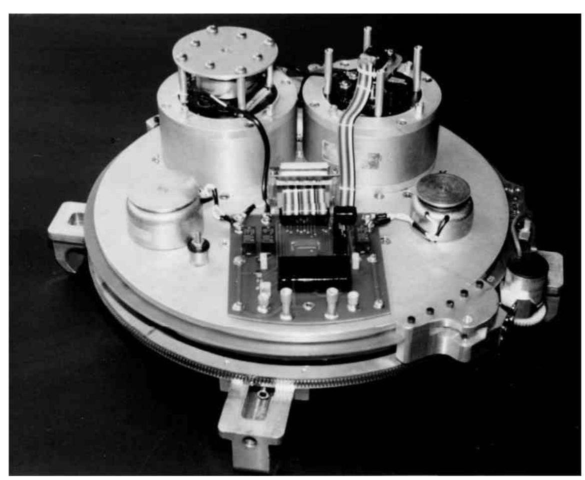

Figure 5: Machine with handwheel disk removed

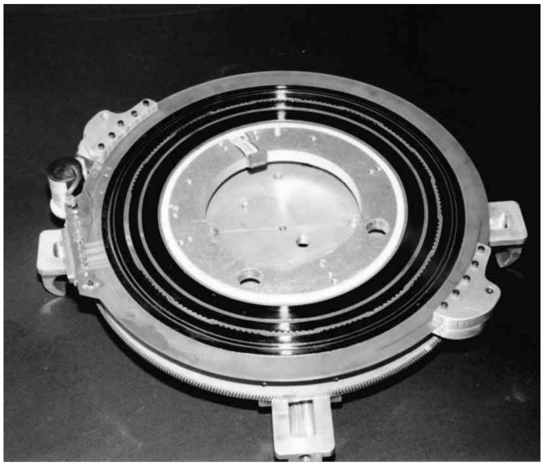

Figure 6: Grounding disk/slip ring assembly

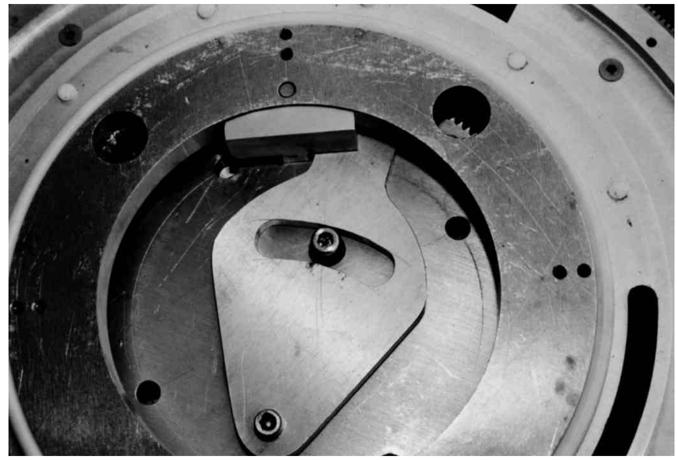

Figure 7: Removable ±180 degree safety stop

ground and signal ground, and also serve as "rotors" for the grounding brake. The disk normally floats between a combination of teflon buttons pressed into the upper and lower motor plate halves and the spring-loaded brushes. When the grounding brake is applied it is squeezed between rubber shoes on the solenoid shafts and rubber crescents in the lower half of the motor plate sandwich.

The grounding disk is fitted with ears for the strut attachment to the vehicle windshield, and a steering wheel angle encoder which is driven by a gear on the driven plate. The gear mesh is spring-loaded to eliminate backlash, by attaching the encoder mounting bracket thru a beryllium leaf.

Figure 7 is a view looking down onto the driven plate attached to the internal gear, showing the removable 180 degree safety stop. The stop pin is a rubber cylinder mounted on a large-diameter screw installed thru the bottom of the driven disk.

Figure 8 shows the arrangement of the synchronous "skate key" clamps. Opposite screws have left-hand and right-hand threads. Centering is automatic.

The window in the driven plate is for brush installation.

MOTORS AND GEARING - Two PMI "Servodisc" permanent-magnet motors are used with a single stage gearpass in which the motor pinions drive an internal gear, in order to minimize the machine's length. The internal gear riding in the large-diameter bearing provides bending rigidity. The Kaydon "four-point contact, type X" bearing is designed to take axial, radial, and moment loads in any combination. Gears with 24 diametral pitch and 20 degree pressure angle were chosen for maximum tooth strength based on computations using the Lewis Formula. The pinions have 12 teeth, and the internal gear has 166 teeth, for a ratio of 13.83-1.

The present motors are 61 mm long and each has a mass of 2.41 kg. A recently-introduced PMI motor using rare-earth magnets will eventually replace the present motors, to save 1.6 kg and 38 mm in length.

BATTERIES - Figure 9 shows the battery box with its top and side covers removed. The batteries are of the sealed lead-acid type, for high charge/discharge capability and compatibility with the vehicle's charging system. Batteries of 2.5 amp-hour capacity so far appear to be optimum for the intended use: however, the prototype's battery box was designed to accommodate either 2.5 or the 5 amp-hour batteries shown in Figure 9 as an interim measure.

The batteries are normally in parallel with the

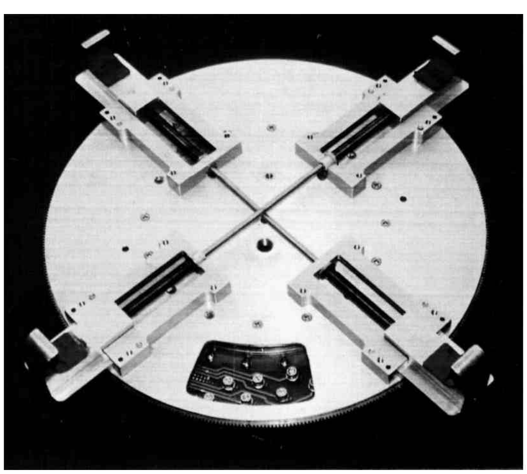

Figure 8: "Skate key" synchronous clamp assembly

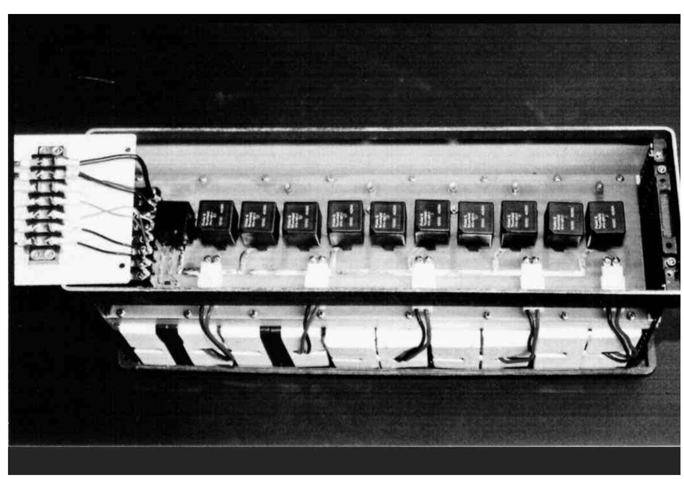

Figure 9: Interior of battery box with 5 amp-hour batteries

vehicle batteries, and are switched into series when the servo amplifier is activated. The motors require 32 volts for back EMF at full speed, and 21 volts for 50 amps across their combined 0.42 ohm terminal resistance. The power amplifier requires 3 volts of overhead at 50 amps. Maximum torque and maximum speed seldom occur simultaneously: however, in series configuration either set of batteries can provide at least 55 volts at 50 amps for short periods, as might be required for fast ramps and maximum steer angle at 5 Hz.

Eleven automotive-type single-pole double-throw relays are used. Ten relays switch the five batteries and the eleventh switches the other ten. The relays are rated for a 75 volt maximum switching voltage and a current capacity of 60 amps at 14 volts. Except for the "dead man" function when the ENERGIZE switch is released in the middle of a run, relay switching always occurs at no load. The actual voltage switched by each relay is that of one battery.

The failure of each relay to energize or de-energize has been analyzed. It is theoretically possible to get reduced voltage on the high-voltage line, and high voltage or reversed voltage on the 12 volt line. The first possibility causes no problem. Protection from the second and third is provided by a clamp diode and an overvoltage protection circuit. These clamp the 12 volt line to ground, which blows the fuses and puts the system into manual control.

POWER AMPLIFIER - The pulsewidth modulated power amplifier is an Advanced Motion Controls Model 50A8. It is designed for supply voltages between 20 and 80 volts. Its internally-limited peak current capacity is 50 amps, reducing to 25 amps continuous current capacity after 2 seconds at 50 amps. Inputs are provided to select current or voltage feedback mode, and to reduce peak current and continuous current capacities. These inputs are utilized by the Program module to set the amplifier characteristics for a given test, or to modify those characteristics during a test by Program Flags. The amplifier is self-protected against short-circuit, overvoltage, and overheating. The unit is usually operated in current mode, in which motor current is proportional to servo error regardless of motor speed.

PROGRAM CIRCUITRY - A crystal oscillator provides the basic 32 kHz clock frequency, which is divided down to form the EPROM address clock frequencies of 2048, 1024, 512, and 256 Hz. The address clock frequency used is selected by two EPROM output lines, and can be changed "on the fly" during a program.

The EPROM has a 18-bit address input. The lower 14 bits are controlled by a counter driven by the address clock, and the upper four bits by the PROGRAM SELECT function of the Control Module. Thus, sixteen separate programs are available, each having 16384 steps at rates of 2048 down to 256 steps per second, in program lengths from 8 seconds to 64 seconds.

The EPROM output has sixteen bits. The lower 12 bits are used in a D/A converter to generate an analog control command signal. The first two upper bits are used to select the address clock frequency. The third is used to inhibit the program counter at any desired point so that it will not begin to repeat if the driver fails to release the PROGRAM switch. The fourth Flag is used to control the power amplifier.

The lower twelve EPROM data bits are fed to a multiplying D/A converter. Here the digital EPROM signal is multiplied by the amplitude/sign signal from the control module. Scaling is ±9.99 volts at ±999 degrees from the Control Module, so an "ALL-ONES" EPROM signal commands a negative 180 degrees steer signal if the Control Module is set at -180.

A second EPROM is included on the Program Module to provide external control signals. It has the same 18-bit address, and an 8-bit output which is buffered and brought out to the front panel as external Flag signals, for turning recording instruments on or uncaging gyros, or operating throttle or brake servos. The external Flags may be programmed as individual ON/OFF signals, as duty-cycle modulated analog signals, or in multibit words.

An alternative program module is available for on-center steer testing, in which the steer is slowly swept through an angle of about ±30 degrees, and the driver might want to remain within lane boundaries. An oscillator feeds an up/down counter, which is connected directly to the multiplying D/A converter to generate a precisely linear ramp position command signal. The ENERGIZE switch energizes the system, releases the failsafe brake, presets the up/down counter, enables the program, and applies the grounding brake. Each momentary application of the PROGRAM switch changes the state of a flip-flop which reverses the count direction, and therefore the direction of the constant steer angle rate. The system provides a linear sweep through center without driver input, but the driver can limit the amplitude of each sweep segment to control the general path of travel. Steer continues until the driver releases the ENERGIZE switch and the system reverts to manual control.

FEEDBACK CIRCUITRY - The 200-count motor encoder is fed thru a 4X quadrature counter and a 16-bit D/A converter to provide a resolution of 0.03 degrees. This voltage is summed with the PROGRAM COMMAND signal to form the servo error voltage. This signal is lead/lag equalized before being sent to the power amplifier.

TORQUE DATA SIGNAL - The current in a permanent-magnet motor is an accurate measure of motor output torque. However, the friction torque from motor brushes, bearing seals, and gear meshes, amounting to about 2 percent of full-scale, creates hysteresis in any attempt to measure torque by measuring motor current. In theory, a signal equal to the total friction torque can be subtracted out from the current signal, leaving only the load torque signal. As a practical matter, variations in friction torque from sources such as geartrain runout still contaminate the measurement, and the method only works if these variations are minimal.

A precision 0.05 ohm resistor is placed in series with the motor leads. The voltage drop across this resistor is a reliable measure of motor current. This voltage is amplified in an isolation amplifier, corrected for motor friction, and made available to the data system. The circuit is located on the Motor Encoder card.

To correct for friction the output of a motor direction flip-flop is conditioned, gain-controlled, and subtracted from the torque signal out of the current isolation amplifier. With the motor running slowly and freely, the "friction signal" is adjusted to produce a zero torque signal output. The efficacy of this correction is discussed in the performance measurement section of this paper.

PART 2: OPERATION

INITIALIZING PROCEDURE AFTER INSTALLATION IN VEHICLE -

1. With the vehicle stopped, depress the Motor Encoder RESET switch. This will eliminate any "surprise" servo error when the system is first engaged.

2. With the vehicle still stopped, depress the ENERGIZE switch. This will put the vehicle under "series servo" control. The vehicle steering wheel/machine handwheel angular relationship will be whatever existed when the motor encoder RESET switch was depressed.

3. With the vehicle still stopped and the ENERGIZE switch depressed, again depress the Motor Encoder RESET switch, and hold it while the second wheel is rotated to line it up with the first wheel. As long as the RESET switch remains depressed, and with zero program command signal (because the PROGRAM switch is not depressed), the servo error remains zero and there is no steering servo motor torque.

4. With the vehicle traveling in a straight line, the steering wheel angle encoder must be reset in the data acquisition system.

TESTING PROCEDURE -

1. The driver selects the steering program, the steer amplitude, and the direction of the initial turn using the hand-held command module. The ENERGIZE switch is depressed, to power the system. The failsafe brake is released, but since in the absence of a program there is a zero angle command and the torque gradient is high, normal driving is possible.

2. Upon reaching the test location and speed the PROGRAM switch is depressed to initiate the program. If the grounding paddle switch is set ON, depressing the PROGRAM switch will ground the handwheel.

Upon completion of the program, the PROGRAM switch is released, centering the front wheels; and then the ENERGIZE switch is released to restore the system to completely manual control and recharge the batteries.

"DEAD MAN" SWITCHING -

1. Releasing the ENERGIZE switch at any time unlocks the ground brakes, locks the motor shaft, and shuts off the servo amplifier. The system is then on manual control at whatever steer angle that was in effect at the time of disengagement. The angular relationship between the vehicle steering wheel and the machine handwheel should remain OK, because of the very rapid engagement of the Failsafe motor brake. The relationship between the vehicle steering wheel and ground is unaffected.

2. Releasing the PROGRAM switch alone unlocks the ground brakes and resets the program to zero. The vehicle steering wheel will immediately attempt to center with respect to the machine handwheel, with the driver supplying reaction torque as ground.

180 DEGREE LIMIT STOP - A stop mechanism to limit motion at 180 degrees is provided as shown in Figure 7. In case of a "hard-over" failure the driver can be expected to involuntarily release the PROGRAM switch, the ENERGIZE switch, or most likely both. This will put him back on fully manual control. The limit stop is meant to prevent steering excursions beyond the driver's recovery ability from occurring within his reaction time. Preliminary machine testing showed that when, with an open-loop step command at 100 km/h the steering went to 630 degrees in under 0.4 seconds; the driver hadn't a prayer of catching it.

The ±180 degree limit was chosen because one of the "rollover immunity tests" in the RSV safety car programs called for a J-turn in which 180 degrees steer is applied at a rate of 500 degrees per second. It is felt that since a driver can input about 120 degrees without taking his hands off the wheel, and 120 degrees with each additional "pull", this represents a reasonable limit.

VEHICLES WITH AIRBAGS - Tests on a 1996 Volvo showed that when an airbag goes off, it can blow the combination of vehicle steering wheel and steering machine completely off the wheel hub, and almost into the rear seats. Before the steering machine is installed, any steering wheel airbags MUST be COMPLETELY DISABLED or REMOVED.

PART 3: SERVO DESIGN

INERTIAL LOAD - The inertial load consists of the motor armature; the internal gear, driven plate, and skate key; the steering wheel and column; and the steering gear, linkage, and front wheels. These are all referred to the driven plate by the square of their respective gear ratios, as listed in Table 1. The total of 126 $g \cdot m^2$ is about half motor assembly and half vehicle steering. The steering gear, linkage, and front wheels represent only 5 percent of the vehicle's inertial load. In the motor assembly, the driven disk and skate key assembly make up 60 percent of the total rotating inertia, and so are prime candidates for weight reduction.

If testing is performed with the steering wheel/airbag removed for safety and replaced by a simple hub, the skate key is not needed and the total inertial load is reduced to about 55 $g \cdot m^2$.

MOTOR TORQUE REQUIREMENTS - A steering wheel torque of 30 N·m is normally considered to be a maximum for measurement of vehicle control response [1]. However, because of the rotating inertia added by the motor assembly the motor torque requirements are considerably higher. The highest torque requirement occurs in frequency response testing, as shown in Figure 10. Inspection of previous testing with manual inputs indicated that an amplitude of ±30 degrees out to 3 Hz has generally been used

TABLE 1 LOAD INERTIAS				
Item	Mass Kg	Inertia g-m^2	Ratio	Reflected Inertia
PASSENGER CARS WITH STEERING WHEEL AIR BAGS				
Average steering wheel*	4.1	53	1	53
2 front wheels		2000	17	6.9
2 tie rods	1.6	25	17	0.1
Rack	2.0	30	17	0.1
Total vehicle with average steering wheel				60.1
STEERING MACHINE				
2 motors		0.08	13.83	15.3
Internal gear		9.6	1.0	9.6
Driven disk	2.6	24.2	1.0	24.2
Skate key	0.9	17.7	1.0	17.7
Total Steering machine				66
* Approximate mass variation between vehicles is 3.6 to 4.6 kg; Inertia variation is 40 to 66 g-m^2 [9]				

in our frequency response testing. To maintain this amplitude to 4.5 Hz requires 50 N·m torque, which has therefore been chosen as a capability level. Torque required increases with the first power of amplitude and with frequency squared, so halving inertia will double amplitude capability at a given frequency or increase frequency capability at a given amplitude by 40 percent if the velocity limit is not exceeded.

MOTOR SPEED REQUIREMENTS - Data from manual-input tests indicates that drivers can input a maximum of 600 degrees per second when turning to a specified angle (e.g., 120 degrees); but they can turn at 1100 degrees per second if they don't have to stop. The difference lies in the need to accelerate and decelerate the handwheel, as opposed to only accelerating it.

In testing protocols, ISO 7401 [1] calls for steer input ramp rates of 200 to 500 degrees per second; and in the international Research Safety Vehicle programs the U.S.ESV and VDA-ESP specifications called for a "rollover test" J-turn with 180 degrees applied at 500 degrees per second [10].

Sinusoidal inputs again impose more severe requirements. At ±60 degrees, 3.5 Hz requires a steering wheel rate of 1318 degrees per second.

To adequately cover all of these requirements, a maximum steering rate of 1800 degrees per second was chosen.

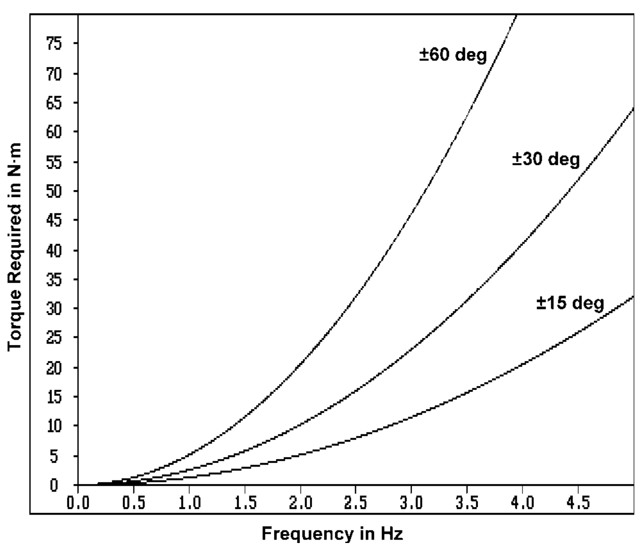

Figure 10: Torque required in frequency response testing

MOTOR RATINGS AND CURRENT LEVELS - Each of the two PMI U9M4H motors has a "momentary" current limit of 79 amps, producing a 2-motor torque of 147 N·m at the driven plate. This is described in the motor manufacturer's data sheet as "the least of the demagnetization limit, the structural limit, and the thermal limit, calculated for maximum pulse duration of 50 milliseconds and 1 percent duty cycle". The current of 79 amps thru the armature resistance of 0.66 ohms produces 4120 watts for 0.05 seconds, or 206 watt-seconds.

For continuous duty at 3000 rpm each motor is rated at 8 amps/0.5 N·m, for a total of 13.8 N·m at the driven plate with 16 amps applied. This rating is based on long-term dissipation of armature heat thru the case to ambient air at 50 watts. For varying conditions the 8 amp rating is the rms (i.e., the root-mean-square "heating" value) current level.

For sinusoidal motion, the peak current required is 40 percent higher than the rms level; so for a continuous sinusoidal steer a peak torque of 20 N·m with 23 amps is permissible. Higher sinusoidal currents can be applied for only short periods because of the limited heat-sink capabilities of the motor armatures.

For servo work in general, high current levels are required only during fast steering wheel motion, such as steering ramps. Figure 11 shows the motor current measured during a 180 degree, 0.1 second ramp. The peak current of 50 amps exists for only 0.2 seconds for each ramp. The rms heating value for each transition is approximately 85 watt-seconds in each motor, which is less than half of the "momentary" rating described above. With a 2 second delay before the second transition, the duty cycle is 10 percent, and the average heat input per motor is 43 watts. The discrete steer inputs used in vehicle dynamics testing therefore should not exceed the motor ratings.

POWER AMPLIFIER - The power amplifier is designed to deliver maximum current for two seconds, after which the current decreases to a continuous level at one-half the maximum. Maximum and continuous current levels can be adjusted downward together, and the continuous level can be further reduced alone.

A relay driven by a Program Flag is used to switch between HIGH or LOW range depending on the program's requirements. In HIGH range the maximum current is always 50 amps and continuous current is set at 20 amps. In LOW range the peak current is adjusted to 30 amps and the continuous level is set at 15 amps. The corresponding steering torques are 50/20 N·m in HIGH range and 30/15 N·m in LOW range.

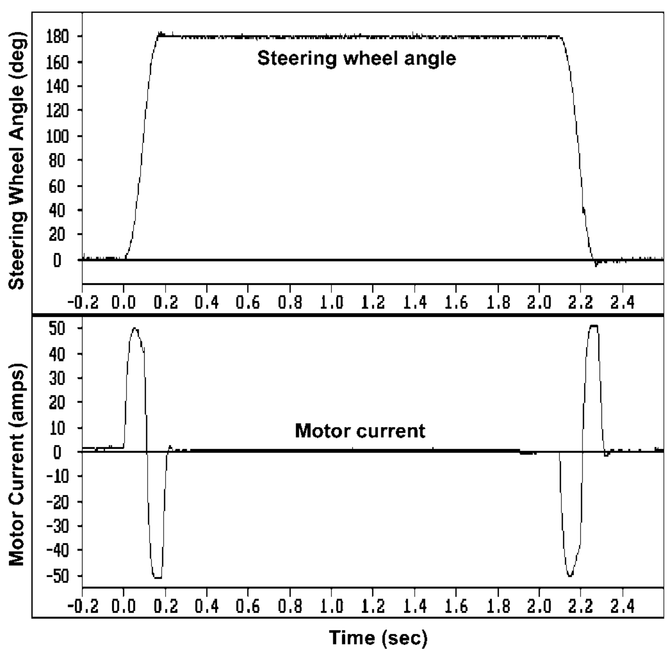

Figure 11: Motor current during 180 deg, 0.1 sec steer ramps

The decay time depends on the rms value of the current delivered during the peak period, so for variable loads it is more than two seconds. The reduction in peak current between HIGH and LOW ranges is adjusted by a potentiometer on the Programmer PC board, and the continuous levels are set by individual resistors.

The maximum/continuous control is a 12-turn linear potentiometer. To adjust the current level it is turned counterclockwise until audible "clicks" are heard; then it is turned clockwise at approximately 4 amps per turn until the desired level is reached. Alternatively, adjustment can be performed using the potentiometer control with a torque wrench on the handwheel. Resistors to set the continuous current as a percentage of the maximum are chosen using a chart supplied by the amplifier manufacturer. For calibration/test the current range can be forced either HIGH or LOW by jumpers on the PC board.

In an evaluation test one motor has been run at continuous stall for 5 minutes with 12 amps, with none of the "stink" which is characteristic of overheating and no after-test performance degradation. At disassembly the armature appeared normal. The current levels chosen are therefore considered to be conservative, and chosen with due respect to "Murphy's Laws".

Peak torque is generally required only for sinusoidal inputs above 3 Hz. Programs for frequency response testing should alternate high and low frequencies to stay out of the current decay regime. For ramp and pulse inputs the response plots look the same in HIGH or LOW range, but in HIGH range the "electronic stops" sound and feel more rigid. While sinusoidal frequency response runs tend to involve 30 seconds of continuous steer with a segment at each of several frequencies, pulse and trapezoidal inputs tend to be of short duration, so the range used is optional. The default range for driving a vehicle with the servo energized and the Program OFF (i.e., zero command) is determined by the program output at zero address. Since 15 N·m is adequate for low-speed driving without power steering, LOW range is preferable.

The amplifier can be operated in either a current or a voltage mode. The current mode results in the very high torque gradient desired for control response work; but it tends to result in a "stepper motor" characteristic feel. The voltage mode, in which the motor's back emf is a damping term, is much smoother, but yields a torque gradient of 4 N·m per degree. The voltage mode was used in "on-center steer" performance measurements because it was smoother.

PROCEDURE FOR NULLING OUT FRICTION- On the motor encoder PC board the current output signal is picked off, amplified, and used to drive a bicolor LED. The LED indicates the direction of sensed torque for all but extremely low current levels. With the output of the steer machine unattached and free to rotate, a slow triangular position command is used to cause slow constant motion in alternating directions, while the friction offset pot is adjusted to zero the torque signal, at which point the LED flickers between red and green or is extinguished.

Figure 12: Test bench setup with barbell weight to simulate a vehicle steering system

PART 4: MEASURED PERFORMANCE IN BENCH TESTING

For developmental testing a barbell weight having a computed inertia of 62 g-m^2 was used to simulate the total steering system of an "average" automobile with airbags. The test setup is shown in Figure 12. The machine specifications developed from the performance testing are summarized in Table 2.

The steering angle resolution is determined by that of the encoder (360 counts/revolution, multiplied by X1 or X4) and the gearing (440/44 gear teeth) between it and the driven plate. Resolution is ±0.025 degrees at 4X and ±0.1 degrees at 1X. The maximum steer angles using a 12-bit data acquisition system are ±50 degrees at 4X and ±200 degrees at 1X. For larger angles the cycle repeats so the data must be pieced together, or the wheel angle encoder must be replaced by one having fewer pulses per revolution.

In the current mode normally used the steering machine has no torque gradient as such. A fast integrator (1 millisecond time constant) in the forward servo loop provides full torque at one-bit position error. In the voltage mode the integrator lies within an inner loop, and so its effectiveness is suppressed: the torque gradient is then 4 N·m per degree.

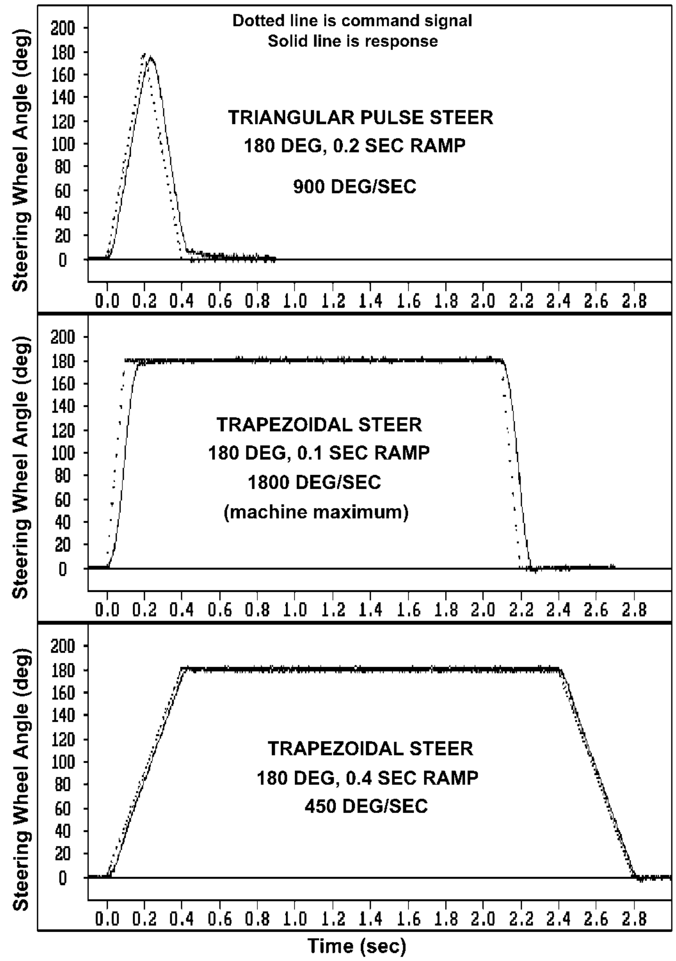

Figure 13: Response to commanded ramps in pulse and trapezoidal steer

Figure 13 shows the steering machine's performance for 180 degree pulse and trapezoidal steer command inputs, with ramps of 0.1, 0.2, and 0.4 seconds.

TABLE 2 PERFORMANCE SPECIFICATIONS		
Steering Angle resolution*	For ±50 degrees: Over ±50 degrees:	±0.025 degrees ±0.10 degrees
Torque Gradient	Current mode: Voltage mode:	Essentially infinite 4 N·m per degree
Torque Capability	For 2 seconds: Continuous:	50 N·m 20 N·m
Maximum Ramp Rate	1800 degrees/sec	
Bandwidth (3 db) **	At ±60 degrees: At ±30 degrees:	4.2 Hz 6.0 Hz
Torque Measurement Accuracy	0.3 N·m	
* With a 12-bit data acquisition system ** With an "average" steering wheel		

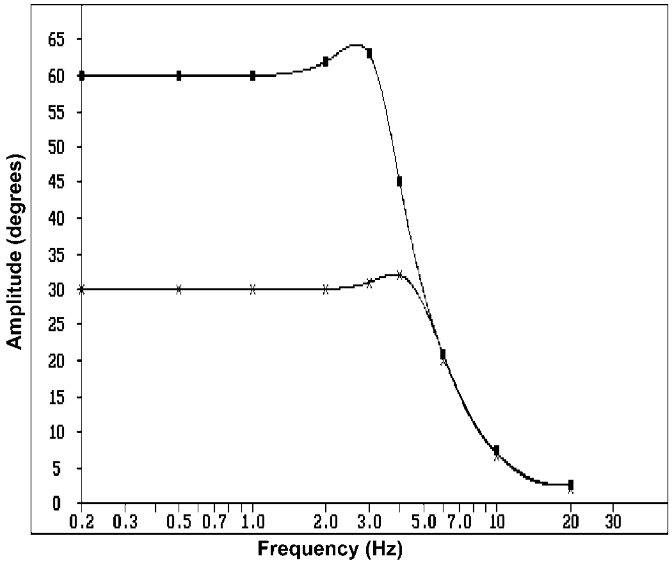

Figure 14: Amplitude response

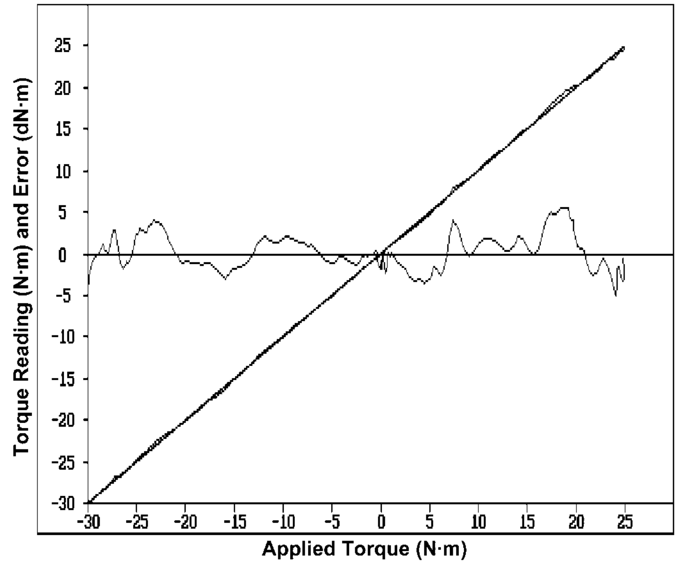

Figure 15: Calibration of stall torque measurement with electronic torque wrench

Figure 14 shows the frequency capabilities for ±30 and ±60 degrees steer, in degrees vs frequency. The bandwidths (-3 db, 0.707 amplitude ratio) are 6 Hz at ±30 degrees and 4.2 Hz at ±60 degrees: bandwidths at other amplitudes can be estimated from the plot.

TORQUE MEASUREMENT - The various ISO Protocols [1,2,6,7,8] recommend measurement of steering wheel torque over a range of ±30 N·m with an accuracy of one percent, or ±0.3 N·m. Accuracies less than those recommended must be noted in any test report. Stall-torque linearity, which is appropriate for fixed-steer testing, was measured with a hand-held torque wrench fabricated with an Interface Model MB25 load cell. With the servo at zero command signal in current mode, torque was applied by hand in both directions. Figure 15 shows the result as torque indicated by the motor current plotted against applied torque as indicated by the torque wrench, which was assumed to be perfectly linear. Also shown in Figure 15 is the deviation from a least-squares linear fit, with 10X scaling (torques in N·m, error in dN·m).

It was noticed too late that the torque applied only went up to 25 N·m in the clockwise direction. In a second test an attempt was made to achieve a smoother input by fixing the torque wrench handle while a small angle triangle command was input to the servo, in voltage mode. When the system was accidentally energized without first zeroing the motor encoder, the load cell was destroyed; and so the hand-held test could not be repeated.

Figure 16: Pendulum test for torque measurement

The maximum deviation from the least-squares fit was found to be ±0.5 N·m, which is in excess of the ±0.3 N·m recommended by ISO. When used in ISO protocols, the failure to meet recommended accuracy must therefore be appropriately noted.

According to reference 4, "Analysis of preliminary trial results indicated that for on-center work an accuracy of ±0.1 N·m was necessary and a range of ±10 N·m was ample." To evaluate the machine's ability to measure while rotating, a weight was mounted on a moment arm attached to the barbell weight, and the machine was mounted vertically as shown in Figure 16. The resulting "pendulum" was driven in voltage mode thru ±190 degrees in a 0.06 Hz triangular waveform, so that velocity was constant in each segment. The load torque was proportional to the maximum moment times the sine of the displacement angle. Maximum torque, at 90 degrees, was 10 N·m. Figure 17 is a plot of torque signal vs. sine of the angle for ±90 degrees of motion: in A with friction not corrected; in B with friction corrected; and in C with friction corrected and frequency-domain filtered at 4 Hz. The friction level in Figure 17A - the difference between clockwise and counterclockwise motion - is ±1.33 N·m. Figure 18 shows the deviation in N·m from a straight-line least-squares fit to the data of Figure 17c, plotted against torque in N·m. Figure 19 shows the friction-corrected and filtered data of Figure 17c re-plotted for the 5 N·m, 30 degrees steer range which is typical for on-center testing [3], along with deviation from a least-squares straight line at 10X scaling.

In the pendulum test the skate key carried a 10 kg load, consisting of the barbell weight plus the pendulum. The

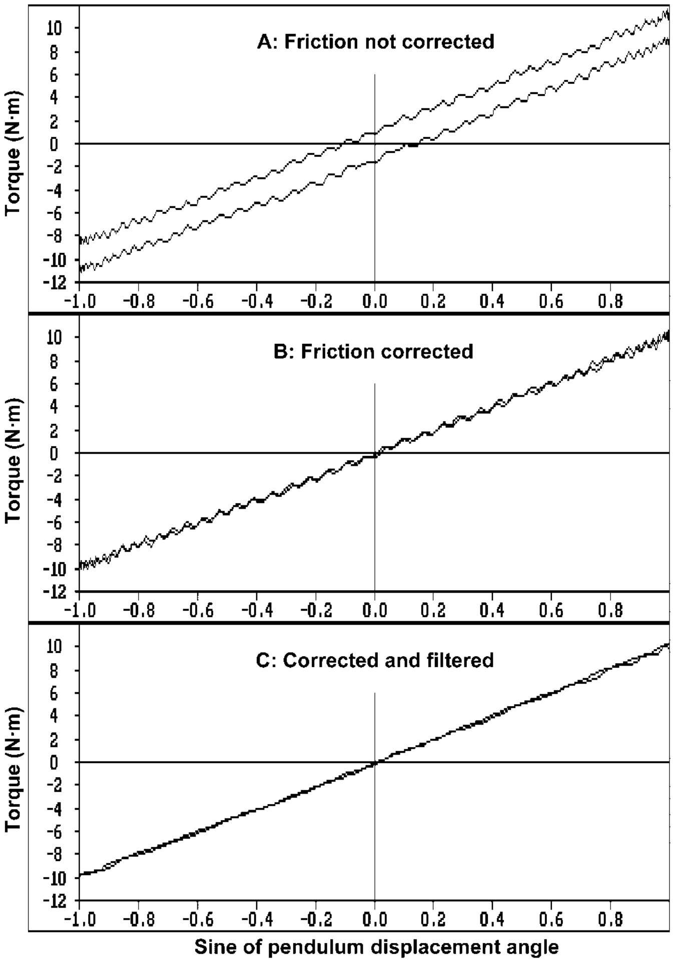

Figure 17: Torque measurement in pendulum test

effect of this load applied to the bearing on variable system friction is not known.

The data in Figures 18 and 19 show a deviation from linearity of ±0.3 N·m over the ±10 N·m range and ±0.2 N·m over the range used in typical on-center testing; so the steering machine will not meet the ±0.1 N·m performance proposed in Reference 4 for on-center testing without further development. The degree of usefulness in its prototype state of development can be judged from Figures 17c and 19.

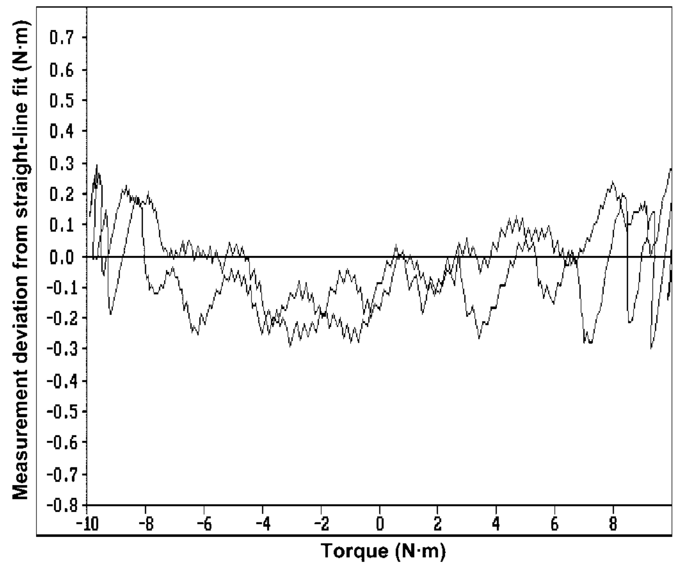

Figure 18: Torque measurement error band

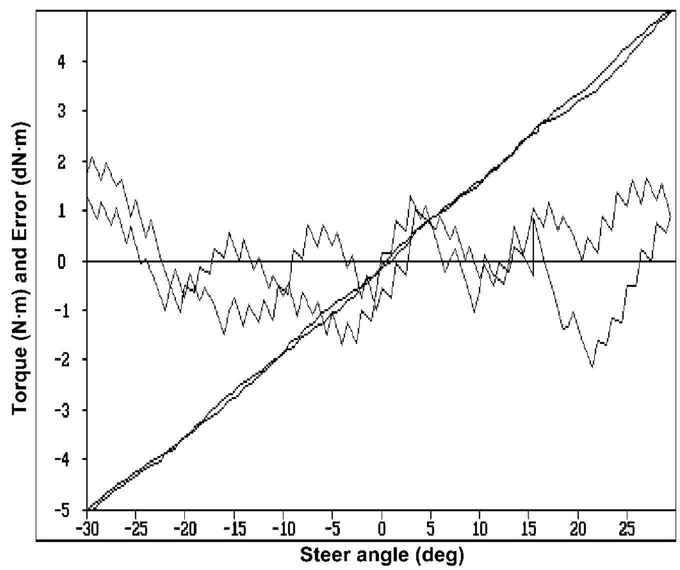

Figure 19: Torque measurement in typical on-center steer range

MECHANICAL IMPROVEMENTS FOR TORQUE MEASUREMENT - The friction level is a combination of motor brushes, bearing seals, and geartooth friction (including that for the steer angle encoder). That due to brushes and seals is at least theoretically constant, and so can be subtracted out as in Figure 17. In Figure 17 the largest part of the friction comes from the bearing seals. Removing them reduced average friction to ±0.66 N·m. This level can be maintained by using shielded rather than sealed bearings. Study of the remaining friction reveals several possible components.

Geartooth friction is dependent on machining inaccuracies, surface finish, and load. The data in Figures 17-19 were obtained with a hobbed and hardened internal gear, and extruded pinions. An initial attempt to improve friction by lapping the gears in place failed because the soft pinions wore quickly while the hard internal gear was unaffected. In discussions with the gear manufacturer it has been decided that lapping-in hardened gears will help some, as will ground-surface gears, finer pitch, and reduced gear thickness.

A load-sensitive error component is logically there, and should show up in pendulum tests as hysteresis; but in pendulum testing up to 30 N·m we have seen no consistent hysteresis pattern. The principle contribution of load appears to be increased sensitivity to other sources of friction.

The steer angle encoder is driven by a gear on the outer diameter of the driven plate, through a leaf spring to eliminate backlash. In the prototype the loading provided by the leaf spring was several times greater than necessary. The total running friction of the bearing and steer angle encoder (with motor and drive gear removed) was measured with a sensitive hand-held torque wrench at about 0.1 N·m The variable portion of this total friction may be tolerably small.

From published data [11] the friction torque for the bearing used, under ideal conditions with 100N radial load at 10 rpm, is 0.16 N·m starting and 0.04 to 0.08 N·m running. The constant value of the running friction can be subtracted out, but that due to non-ideal conditions cannot. In discussions with the bearing manufacturer it was learned that the bearings are not round in the free state but conform to the "shaft" and "housing"; and some subtleties in installation may account for significant variable friction. These measures will be evaluated in a second prototype machine.

Whether these detail improvements can bring the machine's torque-measurement capability to within the recommended limits is at present an unanswered question.

PART 5: WEAVE WHEEL

For on-center testing a dedicated "Weave Wheel" is under development. The design is similar, except that the motor drives the driven plate directly through a flat paddlewheel load cell., attached to the driven plate, so the friction of the motor and gearhead is bypassed. The load cell has six spokes with 12 gauges, arranged to form a 1000 ohm bridge with a gain-of-100 amplifier.

The Weave Wheel uses a smaller motor with a 148-1 gearhead. It uses the same "bottom end", including driven plate skate key, slip ring assembly, and bearing assembly; but a new motor plate and handwheel.

The program is a constant steer rate triangle with the amplitude controlled by the driver on a cycle-by-cycle basis, as previously described.

Testing shows 17 N·m at 10 volts and 10 amps, with a ramp rate of 120 degrees per second - down from 50 N·m at 60 volts and 50 amps with a ramp rate of 1800 degrees per second.

Specification of friction measurement awaits final servo design, but in open-loop testing the friction error appears satisfactory.

With the reduced requirements and the single program, the battery box, electronics box, and control module are eliminated, and the Weave Wheel is self-contained.

PART 6: COMPANION DEVICES: THROTTLE AND BRAKES

The steer machine has eight programmable bits that can be used independently or together to form on/off, duty-cycle modulated, or digital signals. This makes it practical to integrate the steering machine with throttle and brakes to further automate testing in the interest of repeatability. The Electronics Box has two open module slots available for this purpose.

The throttle servo is a modified version of an electric cruise control actuator manufactured by VDO for BMW. The actuator contains a cable reel driven by a geared motor, with a release clutch and a feedback potentiometer. The throttle pull cable is inside a flexible sheath, which can be freely positioned for installation.

The actuator motor is driven by a pulsewidth-modulated servo preamplifier module occupying one electronics box slot and powered by system ±15 volts. The preamp is optically coupled to a 3 amp H-Bridge power stage, located in an external module, run off vehicle 12 volts.

The module uses a speed signal from a fifth wheel, along with external SPEED COMMAND signal and HOLD, or RELEASE signals.

It can also use a throttle command signal from decoded multiple Flag bits, with position feedback from the potentiometer in the servo actuator.

The brake control consists of a ball-bearing lead screw driven directly by a 12 volt Servodisc motor. The output fastens to a LEBOW brake force load cell mounted on the brake pedal, and reaction is through a vertical pad held against the driver seat cushion. Rubber biscuits at each end provide compliance.

The brake control uses a general purpose servo preamp, optically coupled to a 30 amp H-bridge power stage run off vehicle 12 volts. With no signal, the preamp input is biased to give a small reverse voltage. An ON/OFF or duty-cycle modulated flag signal is applied thru an external thumbwheel potentiometer to the preamp input.

The average motor voltage to the actuator drive motor may also be controlled by applying a two-bit duty cycle modulated Flag signal (apply or release, never both together) directly to the H-Bridge.

The amplifier works open loop. The efficiency of the lead screw is over 90 percent, so that open-loop control appears to be satisfactory for most applications.

PART 7: USE IN STANDARD TEST PROTOCOLS

SAE J266 Constant Steer Angle Test [5] - In this test steer angle is kept constant as vehicle is run at several stepwise increasing speeds, or at a speed which increases at a slow constant rate.

When the Steering machine is used, the program controls the steady-state speeds by controlling throttle opening.

The steer angle is set by driving around the minimum circle at idle speed to determine the steering wheel angle required. Then that steer angle is selected in the Command module.

The program can be run in two ways. In the incremental method, four bits of flag signal can be decoded into sixteen levels of throttle. The program increments throttle position command in steps, at eight second intervals.

Eight seconds allows the vehicle to reach steady state and stay there for a measuring interval, but at higher lateral accelerations tends to heat the tires. Therefore three program sequences are needed, with eight, five, and four steps each, with space between each for tire cooling.

The continuous acceleration method is faster in order to limit tire heating. Eight flag signals are decoded to provide a uniform 64 second, 256 step throttle ramp signal.

In either case, the throttle is closed at the end of each program segment by the program, or it can be closed at any time by tapping the brake pedal. In either case the steer is held in while the vehicle coasts to a stop.

SAE J266 Constant Speed, Variable Steer Angle Test [5] - At the test speed the steering wheel is turned to selected fixed values and held until steady state data is obtained. The steer program provides full-scale trapezoidal inputs at 0.1 or 0.2 second ramp rate. Steer angle and direction are selected by digital thumbwheel switches in the Command Module. The steering machine replaces an adjustable steering stop.

ISO 7401 Step Input Test [2]- At the test speed, from an initial straight and steady condition, the steering wheel is turned against a stop at a steer rate between 200 and 500 degrees/second and held there, with throttle held constant, while transient response data is obtained. The steer machine provides full-scale trapezoidal inputs with precisely repeatable inputs; and also provides a "lock throttle" signal to a throttle servo.

ISO 7401 Single Cycle Sinusoid Test [1,2] - At the test speed, from an initial straight and steady condition, a single cycle of sinusoidal steer is input, with "less than five percent amplitude error". Runs are made at 0.5 Hz and 1.0 Hz, at selected amplitudes up to the vehicle stability limit. A steering machine is required for this test.

ISO 7401 Pulse Steer Test [1] - At the test speed, from an initial straight and steady condition, a triangular waveform steering wheel input is applied, with a pulsewidth of 0.3 to 0.4 seconds, followed by a 3 to 5 second neutral steering wheel position. The amplitude is that required to produce a 4 m/s^2 lateral acceleration. The steering machine can provide this steering input in precisely repeatable fashion, with amplitude and direction selected by Control Module switches. If desired, ramp rates can be reduced to 0.1-0.2 seconds, to provide better high-frequency harmonic content.

ISO 7401 Continuous Sinusoid Input Test [1] - At the test speed at least three periods of sinusoidal steering wheel input are applied with predetermined amplitude and frequency. The steering frequency is increased in steps up to 4 Hz. Amplitude ratios and phase lags of various motion variables with respect to steer inputs are obtained from time domain analysis (omitting the first cycle as a transient response). The analysis does not require the vehicle response to be restricted to the linear range. The steering machine is easily programmed to perform this test efficiently. Twenty data points can be obtained from three thirty-second runs.

ISO 7401 Random Input Test [1,6] - At the test speed continuous random steering inputs are made, with amplitude levels sufficient to produce lateral accelerations of approximately 2 m/s^2. Fourier analysis is used to compute amplitude ratios and phase lags: therefore lateral accelerations must not exceed the linear range of vehicle response. Usually 12 minutes of data is required, either continuous or pieced together or averaged 30 second runs, to assure sufficient coherence.

The steering machine can be programmed to produce pseudo-random inputs, with sequences designed to achieve sufficient coherence with maximum efficiency.

ISO 7975 Braking in a Turn Test [7] - The vehicle is driven in a circular path at the test speed, with steering wheel and throttle position fixed. After several seconds of steady state turning the throttle is closed and braking applied. The brake pedal force is held constant at a preselected level with the steering wheel fixed until the test is finished. The test is run at successively higher speeds and brake force levels. A number of transient motion variables are recorded.

In this test the steering machine is used in conjunction with brake and throttle servos. When the desired test speed and radius are established the program is engaged. The steering wheel is fixed (grounded, with zero servo command), and one program flag output fixes the throttle by cutting off throttle servomotor current while keeping the release clutch engaged. After three seconds a second program flag output turns on the brake force servo and releases the throttle servo clutch. Brake pedal force and steer angle remain fixed until the run is finished or the ENERGIZE or PROGRAM switch is released.

ISO 9816 Drop-Throttle Test [8] - The vehicle is driven in a circular path at the test speed, with steering wheel and throttle position fixed. After several seconds of steady state turning the throttle is released, while the steering wheel remains fixed until the end of the run. The steering machine is used in conjunction with the throttle servo. When the desired test speed and radius are established, the program is engaged. The steering wheel is grounded, and the throttle is fixed by a program flag output. After three seconds a second program flag releases the throttle servo clutch, which immediately closes the throttle. The steering wheel remains grounded until the run is over or the ENERGIZE or PROGRAM switch is released.

On-Center Weave Test [3,4] - At the 100 km/h test speed a sinusoidal steer input is applied, with amplitude sufficient to produce 0.2 g lateral acceleration peaks and frequency 0.2 Hz. Steering angle, steering torque, vehicle speed, and yaw velocity are measured and analyzed. A constant low frequency sinusoid is very difficult to generate by hand, but it is very simple with a steering machine. A precise, linear ramp triangular wave, which the machine can generate but a human cannot, should produce more accurate results and will permit lane-keeping corrections by the driver. The steering machine's torque-measuring capability at very low torque levels may not be adequate for this test, unless nonlinearities are measured and removed in data processing.

"Heitzman-Pocobello" Deliberate Tip-up - While the vehicle is driven in a straight line at 45-50 mph the throttle is released and the vehicle begins to coast down. When the speed reaches 40 mph a manual left-right steer input is initiated. The approximate steer sequence is 140 degrees left steer, with a short pause followed by 180 degrees right steer. Actual levels and timing to cause tip-up by roll/lateral acceleration synergism are established manually by "feel". In some cases the response times of lateral acceleration (centripetal plus sideslip rate) and roll are too disparate, and roll response must be obtained by jabbing the brakes. With manual control inputs the test is never precisely repeatable, and so the role of abnormal tire wear in the test results cannot be evaluated.

With the steering machine the control inputs for each run in which tip-up is obtained can be programmed to test repeatability with new tires, and systematic variations in the program can test sensitivity.

SUMMARY

A programmable steering machine has been developed for use in handling response testing. The design aim was to provide a capability for a wide variety of precise, repeatable steering inputs for systematic testing, at levels of force and velocity up to and beyond human limits. Ability to measure handwheel torque as required by several ISO protocols was a second goal. As a third goal, it was hoped that in addition to very high force and velocity levels, the machine could provide the precise steer angle and torque measurements at the extremely low levels required for on-center steer studies. All of these capabilities were to be combined in a self-contained system that could be easily and quickly installed without vehicle modification.

These goals have been substantially, but not entirely, met. Trapezoidal inputs with fast ramp rates; well-defined pulse inputs, and sinusoidal frequency response goals have been met. A practically-infinite torque gradient such that step-steer inputs are unaffected by load has been achieved. The ability to measure steering torques in general testing has been established. Reliability seems satisfactory, in that no failures occurred during one month of continuous closed-loop laboratory testing. Both mechanical and electronics mechanizations are simple and straightforward.

At the present state of development, torque measurement capability is not satisfactory. The recommended ±0.3 N·m accuracy level for ISO tests is not reached. For on-center steer testing the machine offers the precise sinusoidal or triangular steer generation that is needed along with sufficient accuracy and resolution in steer angle measurement, but its torque measuring capability is not yet satisfactory. Whether the required accuracies can be attained (and maintained in the "real world" as opposed to the laboratory) by improvement in design details is at present an unanswered question, and is the subject of ongoing research.

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