THE HUMP IN ROLL RATE FEEDBACK:

SOURCE AND COUNTERMEASURES

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INTRODUCTION

Reverse-steer testing: whether called by that name (ATI); Fishhook (Toyota, NHTSA): or Road Edge Recovery (NHTSA) has become the primary test for vehicle rollover. Steering Machines first introduced by ATI/Heitz in 1996 have made Reverse Steer testing precise and repeatable. The problem of "timing" the steer reversal without favoring one vehicle over another was essentially solved by ATI's introduction of roll rate feedback in June of 1998. With roll rate feedback the steer reversal begins when the roll rate signal enters a window comparator around zero roll rate, at maximum roll angle. This method does not discriminate for or against vehicles having fast or slow roll response, since steer reversal is at max roll angle for all.

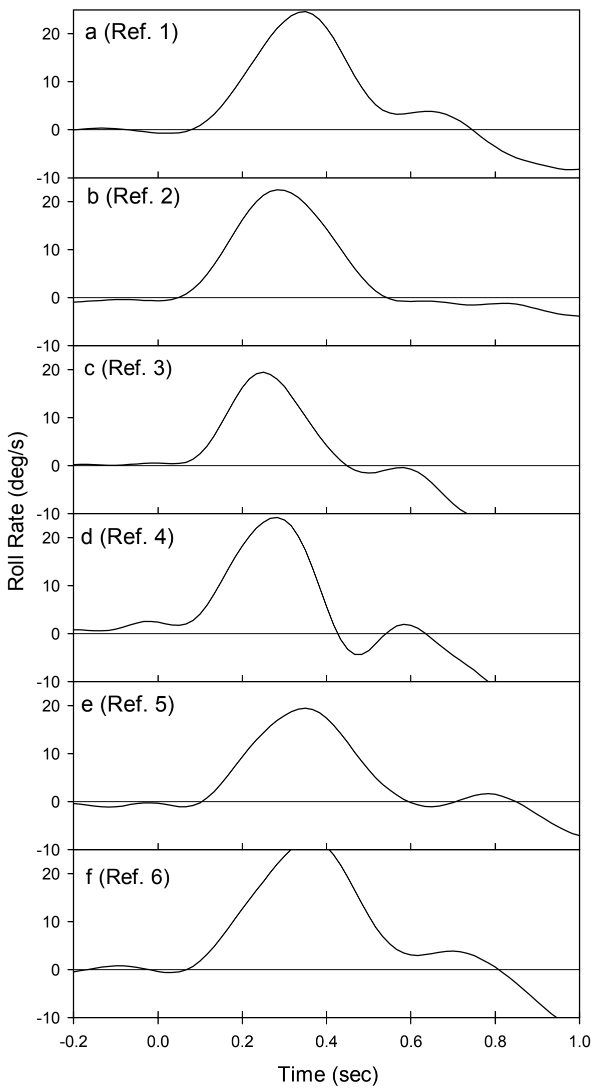


Figure 1: Sample roll rate responses

HUMP PROBLEM DISCOVERED

A peculiar problem was soon discovered in testing: the roll rate does not pass through zero cleanly. In practically all test runs there is a secondary oscillation, called a "hump", near zero. Figure 1 shows the roll rate response in reverse steer testing of several vehicles.

The hump may be centered at zero, or it appear below or above zero. When it happens sufficiently above, the signal can miss the zero window as in Figure 1a, and the steer reversal is delayed. The phenomenon was discovered in testing of the early Geo Tracker, both at NHTSA and at ATI. It was first thought to be caused by early engagement of the bump stops in the Geo front suspension. But then the hump was noticed in other testing, almost always at or below zero where it didn't cause noticeable delay. The sloughing off in some runs such as Figure 1B is thought to result from loss of adhesion in the loaded front tire.

The hump was also found in ATI's frequency response testing with large steer angles as part of an ISO task force on vehicle behavior at high lateral acceleration (Reference 7). In testing of a 4-door, 4WD Suzuki Sidekick the roll rate response looked totally distorted at 0.4 Hz; the hump appeared at 0.8 Hz and 1.0 Hz; and the distortion was gone at 1.2 Hz. (Figure 2). With increasing steer amplitudes at 1 Hz, the hump tended to move downward with increasing hump amplitudes (Figure 3).

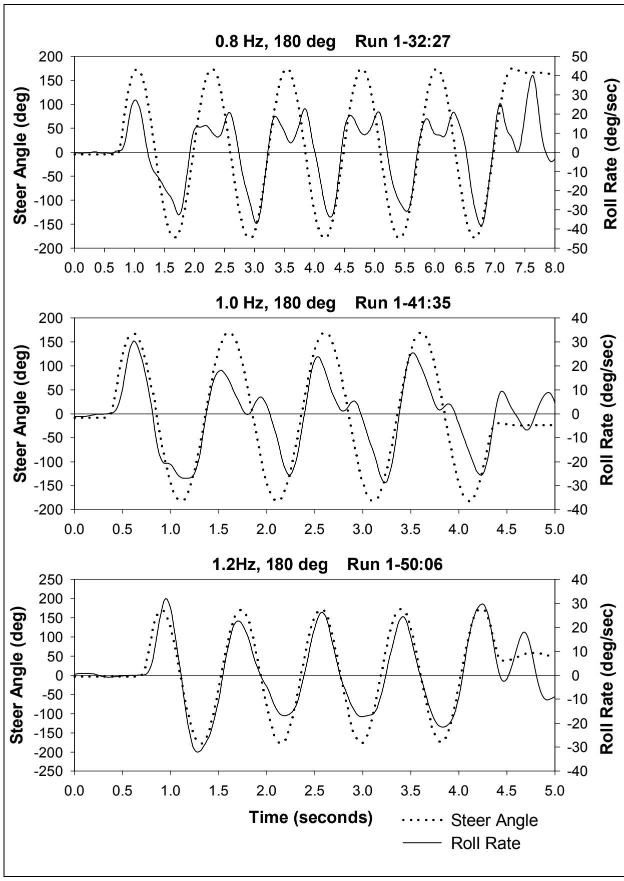


Figure 2: Steer frequency effect

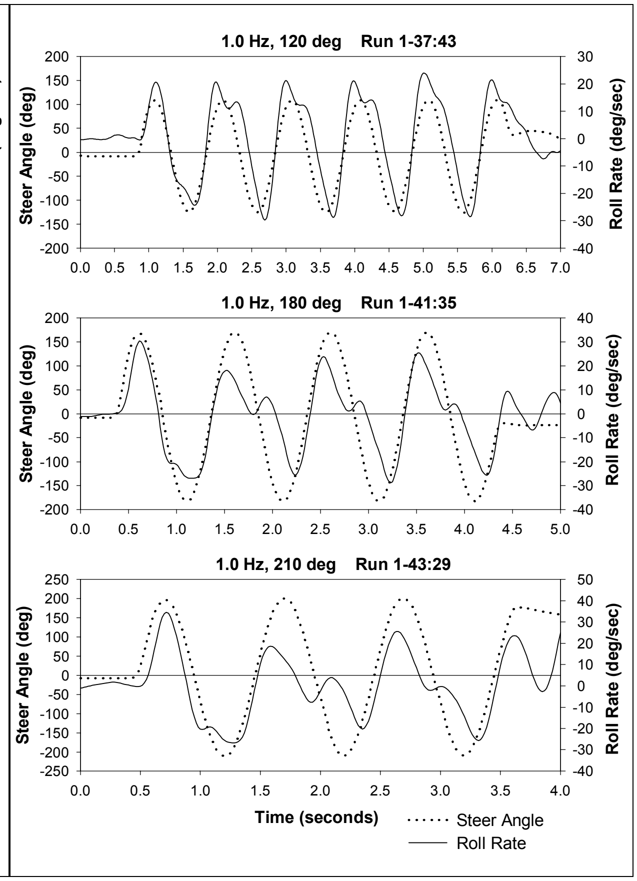


Figure 3: Steer amplitude effect

HYPOTHESIS

It was then hypothesized that the phenomenon was a combination of sprung mass rotation about the roll axis and total vehicle rotation about the tires as a fulcrum.

The accidental discovery of the hump picture on the cover of the softback version of Den Hartog's *Theory of Oscillation* (Figure 4) reinforced this hypothesis. The cover picture, which also appears as Figure 1.17 of the Den Hartog text, graphs the expression $x = a \sin \omega t + a/2 \sin 2\omega t$. Vehicle roll rate responses looked remarkably like this combination of a fundamental frequency plus a second harmonic. Figure 5 demonstrates the effect of hump amplitudes relative to the "fundamental", and Figure 6 demonstrates the effect of changing the relative frequencies. If the harmonic frequency greater than twice that of the fundamental the hump is higher; if twice the hump is at zero; and if less than twice the hump is lower. All of the patterns seen in vehicle testing can be constructed within a narrow range of frequency and amplitude ratios.

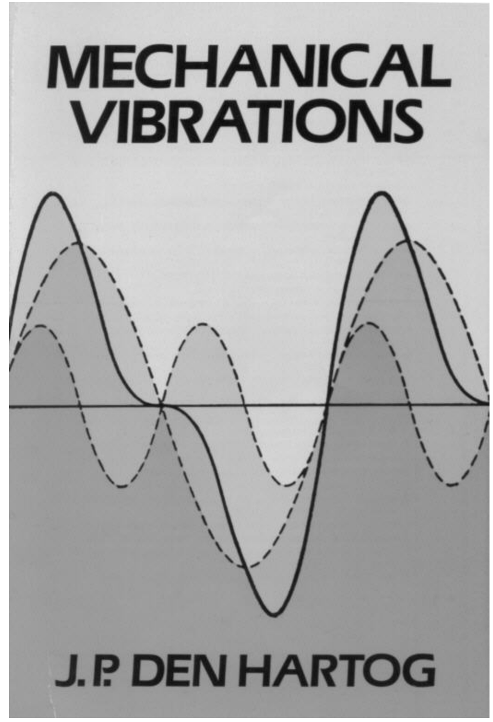


Figure 4

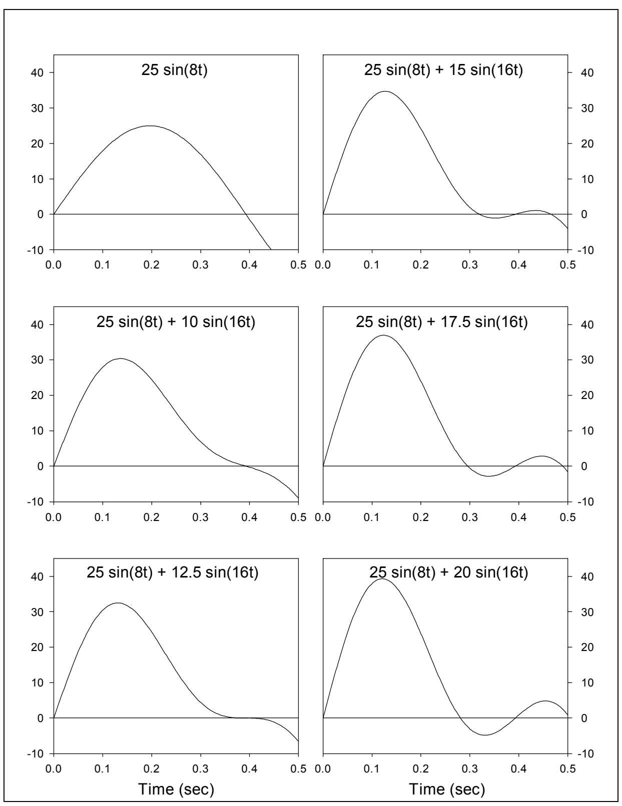


Figure 5

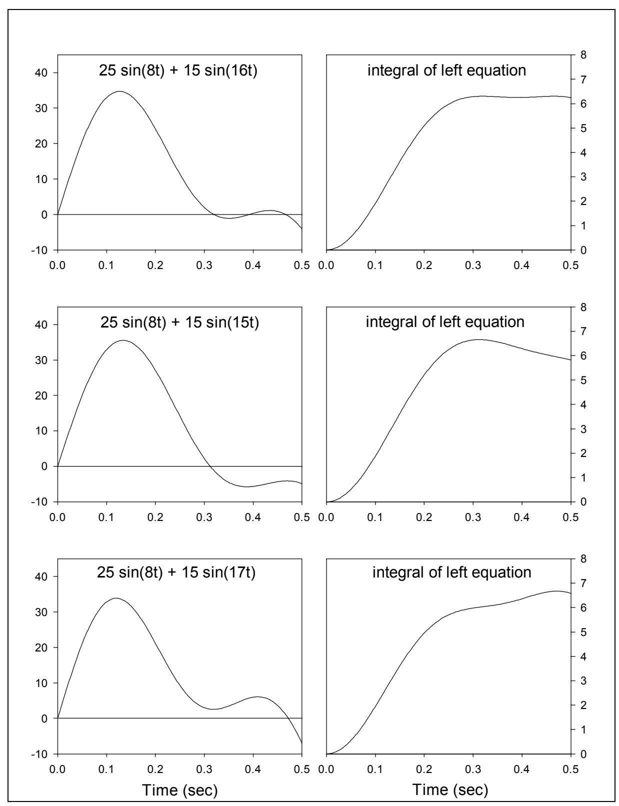


Figure 6

APPROXIMATIONS TO FREQUENCIES

For a simple second-order system the time to first peak in response to a theoretical step input is the inverse of one-half the damped resonant frequency. In real life, roll rate response is not so simple.

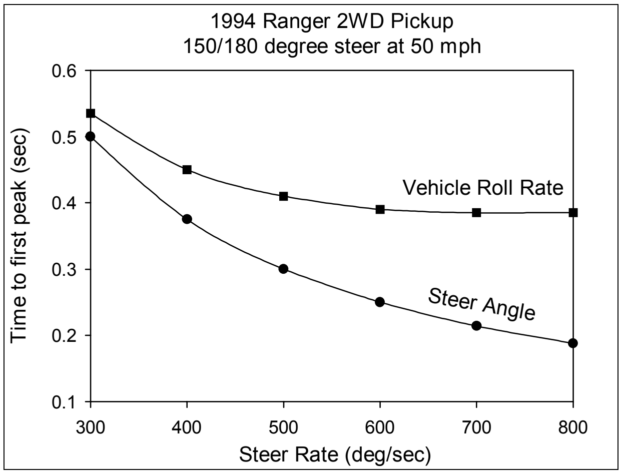


Figure 7
Time to first peak of Steer and Roll Rate

First, it depends on the magnitude and rate of the steer input. Figure 7 shows the time to first peak for a Ranger 2WD pickup at different steer rates, for 150/180 degrees left/right steer at 50 mph (Reference 9). As the steer rate increases the response becomes more and more like response to a step input. The indicated "step response" at 800 degrees/second steer rate equates to a damped resonant frequency of 1.3 Hz. Second, tire saturation "mushiness" will reduce the relative total vehicle frequency, as indicated in Figure 3. Third, the presence of the second harmonic shortens the apparent half-sine of roll rate as shown in Figure 4, and thus increases the apparent frequency. Nevertheless, the nonlinear roll frequency can be *approximated* from the zero-crossing of the roll rate trace.

The roll inertia of the total vehicle is 2-3 times that of the sprung mass, and the tire spring rate may be 10-12 times that of the sprung mass roll rate. Thus, from "the square root of k/m" we have a reasonable "fundamental" and "second harmonic" frequency combination. The amplitude of the total vehicle oscillation relative to that of the sprung mass may seem high; but remember that rim strikes sometimes occur. Also, the total vehicle oscillation is at a higher frequency, which means a higher rate at the same amplitude, and is less damped. The departure from "twice" is what raises or lowers the hump from the zero axis.

HUMP COUNTERMEASURES

Having identified the problem, there were three possibilities that could be considered. First, the zero window could be widened. Considerable widening might be necessary, which would tend to reduce the steer pause in all runs. Second, limit the pause length to some arbitrary value. This tends to be against the whole idea of letting the vehicle find its own steer reverse point. Third, filter the roll rate signal.

Since the hump frequency is always reasonably close to twice the "fundamental" it can easily be affected with electronic filtering. By filtering the hump can be removed, or it can be accentuated.

HUMP SUPPRESSION

Analysis of data from several vehicles indicates that a range of frequencies from 1.1 to 1.6 Hz should be passed and frequencies above 2.2 Hz should be suppressed. A simple low-pass filter cannot be made to work because its phase lag cannot be compensated by any physically-realizable circuit. After trying several different types, it was decided that a single-stage *bandpass* filter with a center at 1.2 Hz and a Q of 1 (3 db bandwidth 0.6 to 1.8 Hz), would be effective. Figure 8 shows the effect of this filter on the test run humps from Figure 1. A circuit diagram, response plots and mathematics for this filter are given in Appendix A.

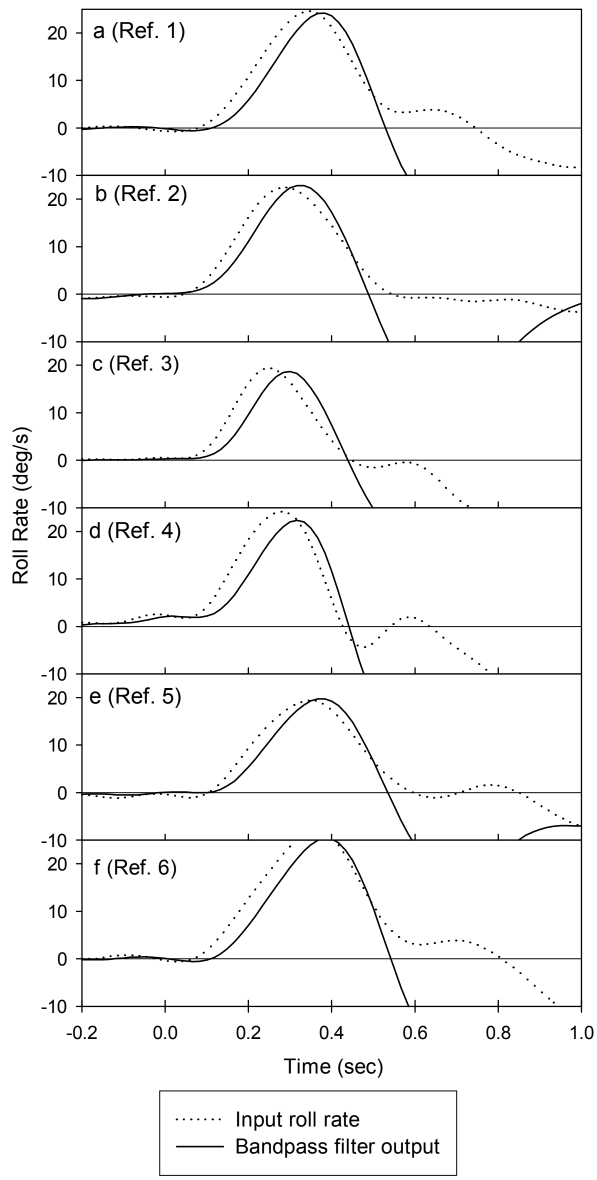


Figure 8
Bandpass filter effect

HUMP ACCENTUATION

A stronger hump has a better chance of reaching the window boundary. This can be accomplished by a simple "lead network" which increases amplitude at a nominal rate of 6 db/decade, or a factor of 2 between fundamental and hump amplitudes. As shown in Appendix B, the 6db/octave is attained in the linear section midway between the two break frequencies, and lesser differences are attained near the breaks or when the breaks are brought closer together. The phase shift associated with the lead network is compensated by means of an "all pass" filter with constant amplitude and increasing phase lag.

Figure 9 shows the effect of a moderate filter with breaks at 1.3 Hz and 5.3 Hz.

Circuit diagrams, response plots and mathematics for the lead network and the with phase compensation filter are given in Appendix B.

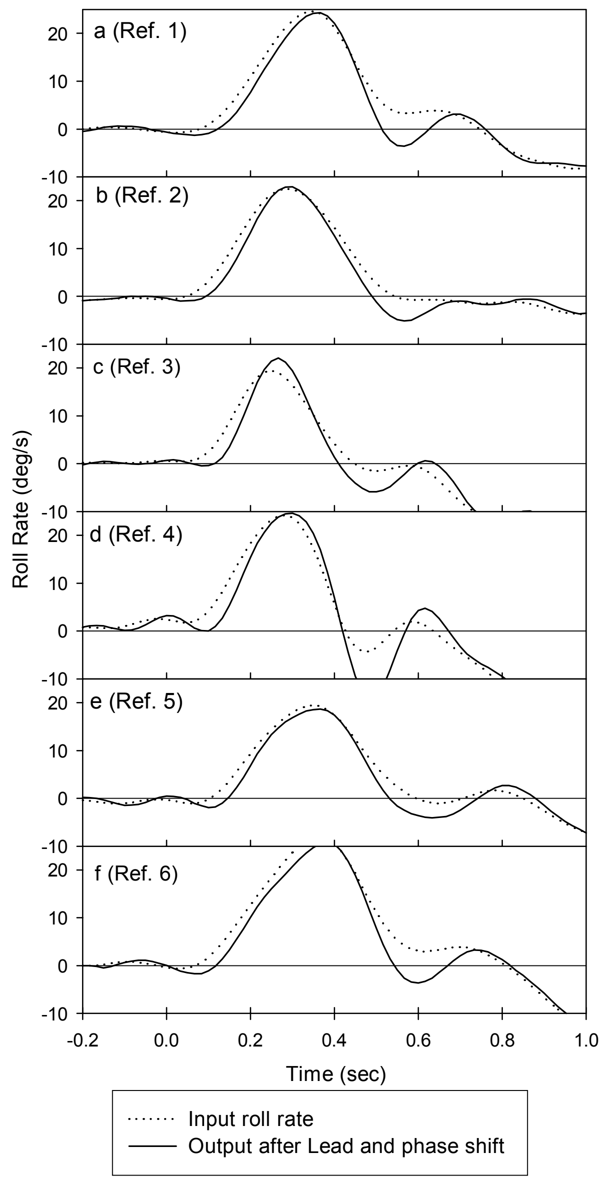


Figure 9
Lead and Phase shift effect

FILTER PERFORMANCE

Hump removal and hump suppression are both capable of eliminating the occasional extended pause before steer reversal. The bandpass filter is considerably more definite, while the lead network retains the general shape of the original roll rate plot. Because it is more definite and does not require phase compensation the bandpass was chosen for hardware implementation (box shown in Figure 10); and when recorded data was played through it the results were as predicted. The box implementation has provision for passthrough of the original signal to the data system, and switch-selected original or filtered signal to the steering machine. The circuit diagram is in Appendix 1.

ARE ANY COUNTERMEASURES APPROPRIATE ?

The countermeasures described above are capable of eliminating the occasional excessive pause before steer reversal. But should they be used? All countermeasures tend to slightly reduce maximum roll angle at steer reversal, whereas the uncompensated maximum roll angle is accurate. Furthermore, uncompensated maximum roll angle appears to have a greater total vehicle-tire component, which has greater potential energy. Also, the increased delay results in a greater sideslip angle and a greater speed scrub-off at steer reversal, which tend to opposite effects on maneuver severity. On balance, it can be strongly argued that the vehicle should be "left alone to do its thing".

RECOMMENDED OPERATION

In reversed steer testing the driver immediately notices the increased sideslip and path deviation when steering reversal is significantly delayed. In normal operation the filter is therefore left out, and if a delay is noticed in a given test run that run is repeated with the filter switched in. The results of the two runs can then be compared.

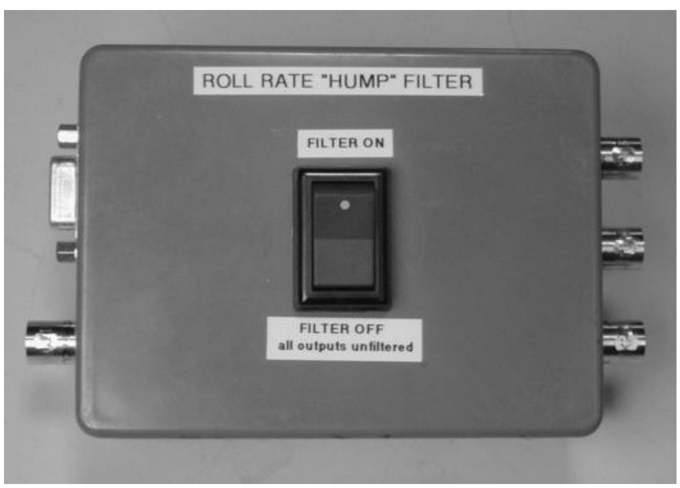


Figure 10

REFERENCES

1. Geo Tracker, 180/180 degrees steer at 50 mph. ATI Test Report No. 082801: *Reverse Steer Testing of 1991 Geo Tracker 4WD* at 2-0:51:25.

2. 2001 Chevrolet Tracker, 180/180 degrees steer at 50 mph. ATI Test Report No. 072401: *Reverse Steer Testing of 2001 Chevrolet Tracker 2-Door 4WD* at 1-0:12:33.

3. 1994 Mazda Pickup, 150/180 degrees steer at 56 mph. ATI Test Report No. 981009: *Reverse Steer Testing of 1994 Mazda 2300 Pickup* at 2-1:11:04.

4. 2000 Pathfinder, 150/150 degrees steer at 50 mph. ATI Data File 101001: *ISO Task Force Testing, 2000 Pathfinder, ATI Protocol* at 4-0:03:59.

5. Loaded 15 Passenger Van, 180/180 degrees steer at 45 mph. ATI Test Report 120700: *Reverse Steer Testing of 1992 GMC RALLYE STX 15-Passenger Van* at 2-0:23:18.

6. 1997 Kia Sportage, 180/180 degrees steer at 50 mph. ATI Test Report 091202: *Reverse Steer Testing of 1997 Kia Sportage RWD* at 4-0:03:05.

7. 1995 Sidekick, sinusoidal steer at 50 mph. ATI Data File 101001: *ISO Task Force Testing, 4WD 4-Door Sidekick, Italian Protocol* at 1-0:32:27, 1-0:41:35, 1-0:50:06, 1-0:37:43, 1-0:43:29.

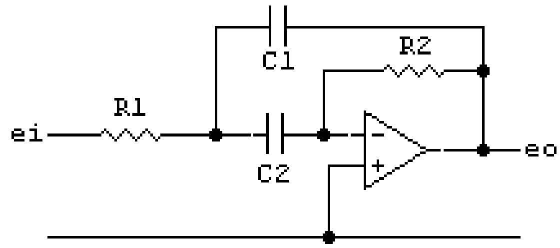
8. J.P. Den Hartog, *Mechanical Vibrations*. Dover Publications, New York. 1985 republication of the 1956 4th edition.

9. ATI Report No. 110700, *Input Study: Steer Rate, Speed/Steer Schedules*, November 2000.

10. D. Lancaster, *Active Filter Cookbook*, Howard W. Sams & Co., Indianapolis Indiana, 1975.

Appendix A - Bandpass Filter

The single stage multiple feedback bandpass filter is described in Reference 10, pages 151-154.



$$\frac{e_o}{e_i} = \frac{\dfrac{-s}{R_1 C_1}}{s^2 + s\dfrac{1}{R_2}\left(\dfrac{1}{C_1} + \dfrac{1}{C_2}\right) + \dfrac{1}{R_1 R_2 C_1 C_2}}$$

Let $C1 = C2 = C \qquad R2 = 4Q^2 R_1 \quad \text{Gain} = -2Q^2$

$$\frac{e_o}{e_i} = \frac{\dfrac{-s}{R_1 C}}{s^2 + s\dfrac{2}{4Q^2 R_1 C} + \dfrac{1}{4Q^2 R_1^2 C^2}}$$

from which $\omega = \sqrt{\dfrac{1}{4Q^2 R_1^2 C^2}} = \dfrac{1}{2QR_1 C}$ and $R_1 = \dfrac{1}{2Q\omega C}$

For $\omega = 2\pi(1.2 \text{ hz}) = 7.5$ rad/sec, and $C = 0.68\ \mu\text{F}$:

$$R_1 = \frac{10^6}{2Q(0.75)(0.68)} = \frac{98039}{Q} \approx \frac{100\text{K}}{Q}$$

at Q=1, R_1= 100K, R_2= 400K:

$$e_o = \frac{\dfrac{-s}{0.068}}{s^2 + 7.35s + 54} = \frac{-14.7s}{s^2 + 7.35s + 54}$$

Figure A1 shows magnitude and phase angle for the filter, normalized by an external gain of 0.5.

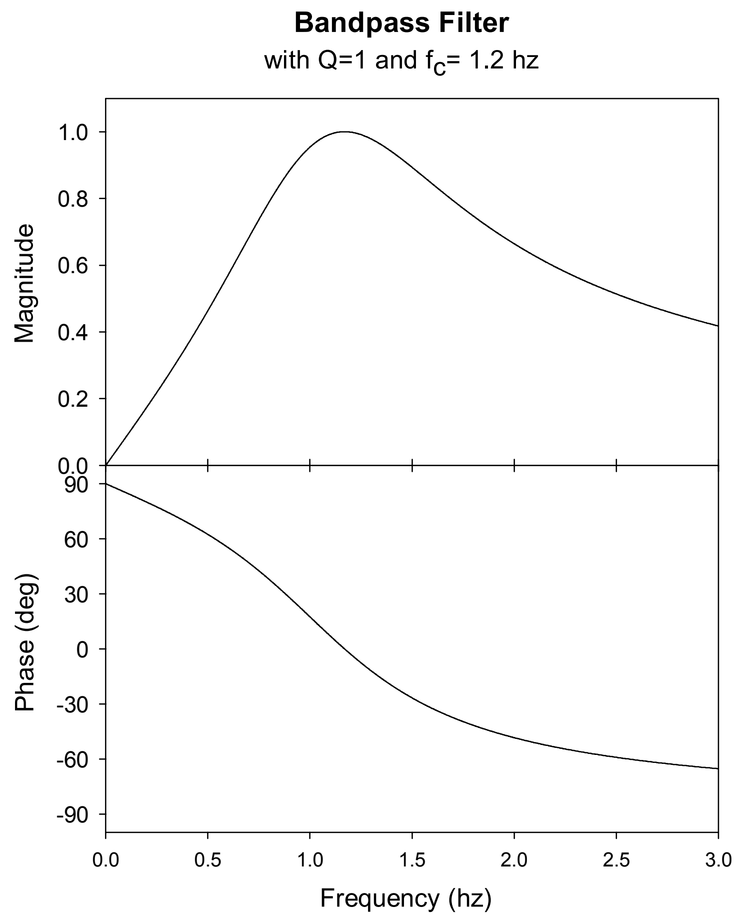


Figure A1
Magnitude and phase plots for selected bandpass filter.

Figure A2 shows a circuit diagram for the filter box, with roll rate pass-through and a buffered switchable output.

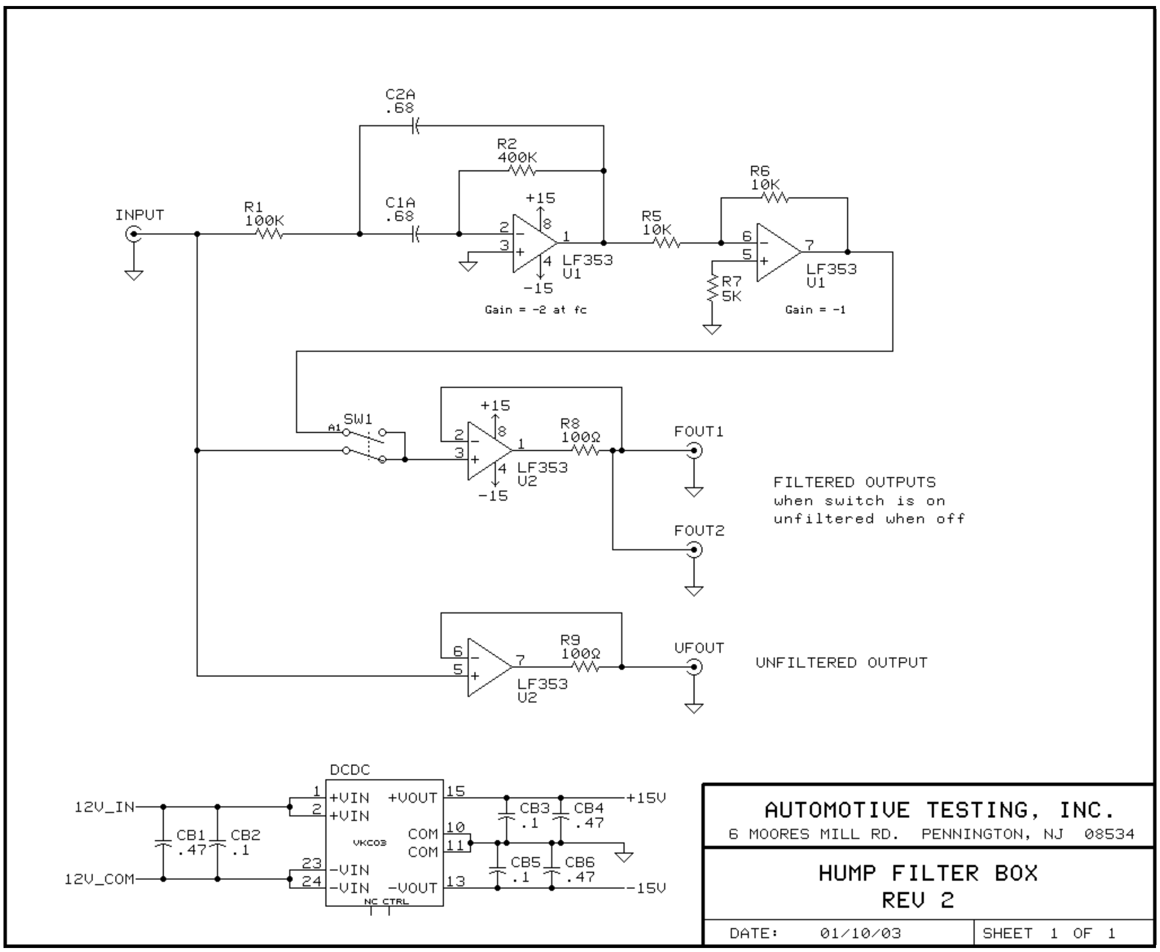
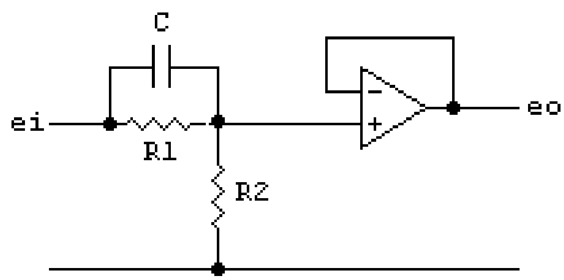


Figure A2
Circuit for bandpass filter box

Appendix B - Lead Network



$$\frac{e_o}{e_i} = \frac{Z_2}{Z_1 + Z_2}$$

where $\quad Z_2 = R_2 \quad$ and $\quad Z_1 = \dfrac{\dfrac{R_1}{j\omega C}}{R_1 + \dfrac{1}{j\omega C}} = \dfrac{R_1}{j\omega R_1 C + 1}$

substituting s for $j\omega$: $\qquad Z_1 = \dfrac{R_1}{1 + R_1 Cs}$

$$\frac{e_o}{e_i} = \frac{R_2}{R_2 + \dfrac{R_1}{1 + R_1 Cs}} = \frac{R_2\left(1 + R_1 Cs\right)}{R_1 + R_2 + R_1 R_2 Cs} = \frac{R_2\left(1 + R_1 Cs\right)}{\left(R_1 + R_2\right)\left(1 + \dfrac{R_1 R_2}{R_1 + R_2} Cs\right)}$$

Let $\; T_1 = R_1 C \quad$ and $\quad T_2 = \dfrac{R_1 R_2}{R_1 + R_2} C$

$$\frac{e_o}{e_i} = \frac{R_2}{\left(R_1 + R_2\right)}\left(\frac{1 + T_1 s}{1 + T_2 s}\right)$$

For $\; T_1 = 0.12$ sec, $\; T_2 = 0.03$ sec,
$R_1 = 1\ \mathrm{M\Omega}$, $\; R_2 = 360\ \mathrm{K\Omega}$, $\; C = 0.12\ \mu\mathrm{F}$

$$\frac{e_o}{e_i} = 0.265\left(\frac{1 + 0.12s}{1 + 0.03s}\right)$$

Figure B1 shows the amplitude and phase response for breaks at 0.5 hz and 5.3 hz ($1/T_1 = 3$ rad/sec and $1/T_2 = 33$ rad/sec). 1 hz and 2 hz are in the linear part, with 6 db/octave, or a 2-1 ratio.

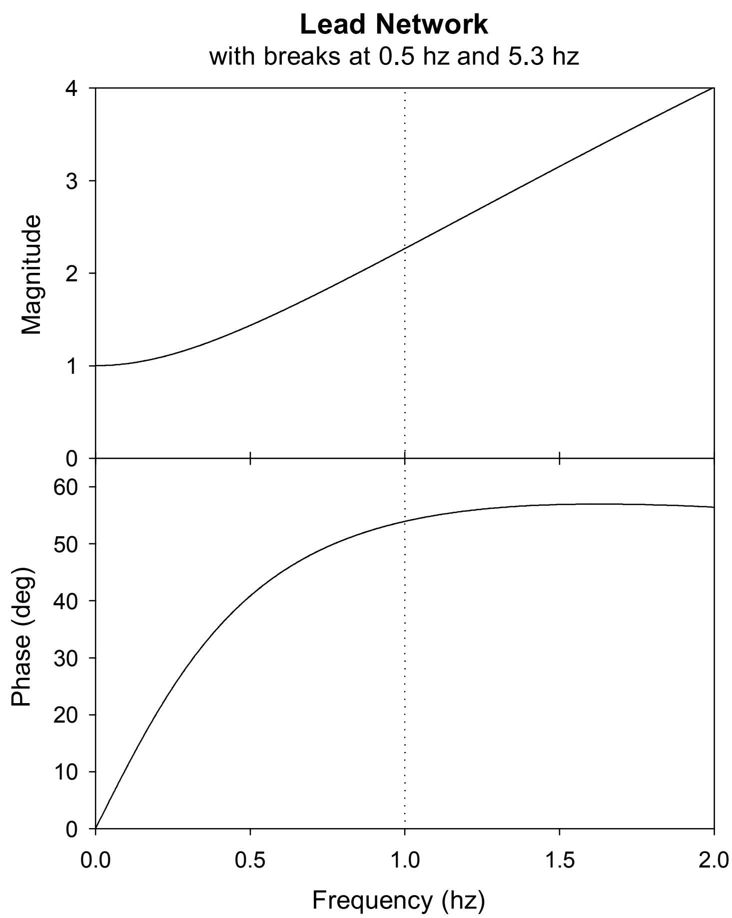


Figure B1
Magnitude and phase response of lead network
with breaks at 0.5 hz and 5.3 hz.

Figure B2 shows the amplitude and phase response for the filter chosen, with breaks at 1.3 hz and 5.3 hz (T_1 = 0.12 seconds and T_2 = 0.03 seconds). The amplitude ratio between 1 hz and 2 hz is reduced to 1.4, or a 40 percent increase in the hump size relative to the fundamental. Figure B2 also shows leading phase shifts of 26.3 degrees at 1 hz and 35.8 degrees at 2 hz. These require compensation by means of the “all pass” filter which provides phase lag at constant amplitude.

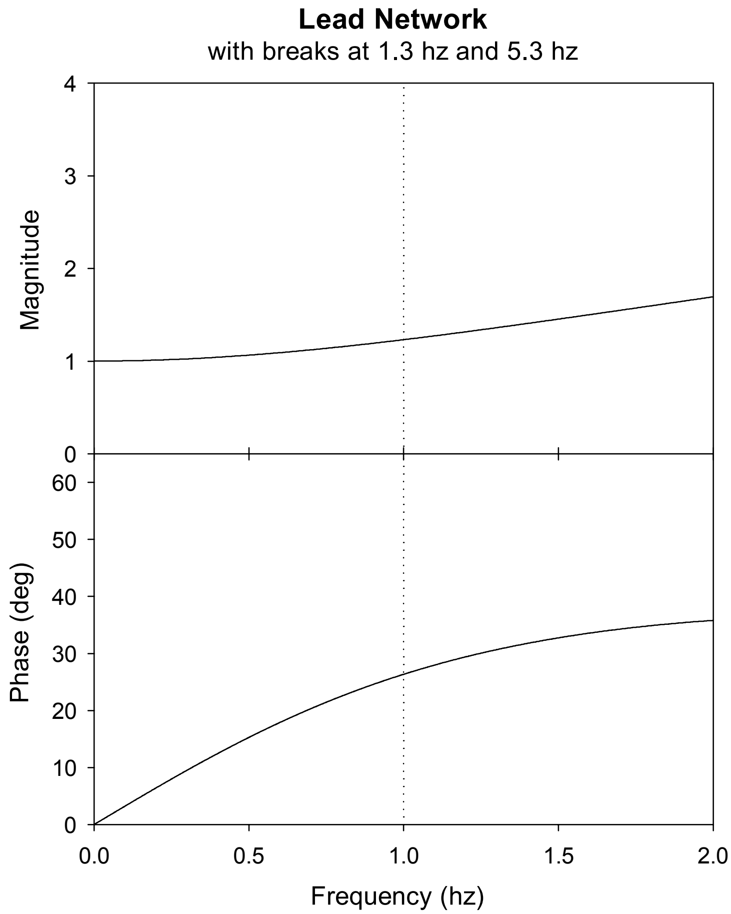
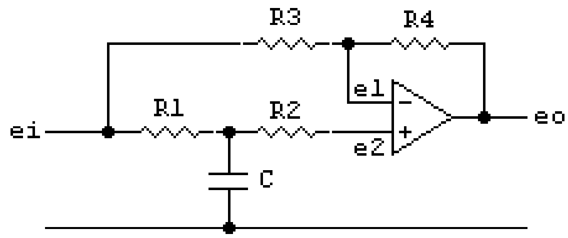


Figure B2
Magnitude and phase response of chosen lead network
with breaks at 1.3 hz and 5.3 hz.

All-Pass Filter



Assume $e1 = e2$, No current across $R2$, All resistors equal $(R = R1 = R2 = R3 = R4)$

$$e_1 = \frac{(e_o + e_i)}{2} \quad \text{and} \quad e_2 = \left(\frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} \right) e_i$$

substituting s for $j\omega$ and equating e_1 with e_2 :

$$e_1 = e_2, \ \therefore \ \frac{e_o + e_i}{2} = \left(\frac{\frac{1}{Cs}}{R + \frac{1}{Cs}} \right) e_i$$

$$e_o = 2\left(\frac{\frac{1}{Cs}}{R + \frac{1}{Cs}} \right) e_i - e_i = \left[2\left(\frac{\frac{1}{Cs}}{R + \frac{1}{Cs}} \right) - \left(\frac{R + \frac{1}{Cs}}{R + \frac{1}{Cs}} \right) \right] e_i$$

$$\frac{e_o}{e_i} = \frac{\frac{2}{Cs} - R - \frac{1}{Cs}}{R + \frac{1}{Cs}} = -\left(\frac{R - \frac{1}{Cs}}{R + \frac{1}{Cs}} \right) = -\left(\frac{RCs - 1}{RCs + 1} \right)$$

For RC = 0.03 sec: $R =$ 100 KΩ, $C =$ 0.3 μF

$$\frac{e_o}{e_i} = -\left(\frac{0.03s - 1}{0.03s + 1} \right)$$

The amplitude and phase response of the all-pass filter is shown in Figure B3 and the combination of the lead network and the all-pass filter is shown in Figure B4.

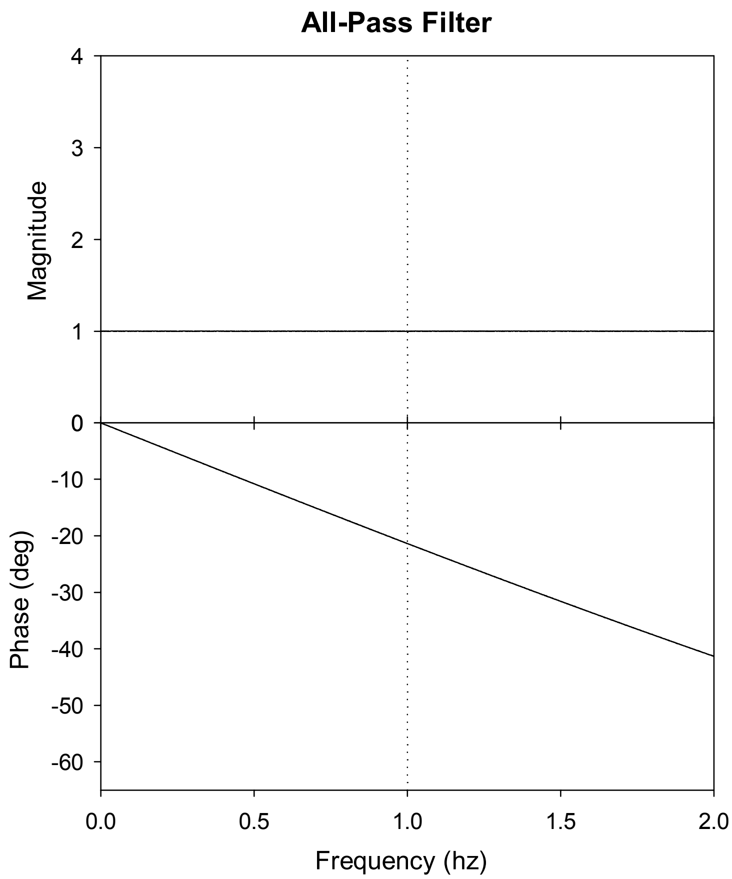


Figure B3
Magnitude and phase response of All-pass filter

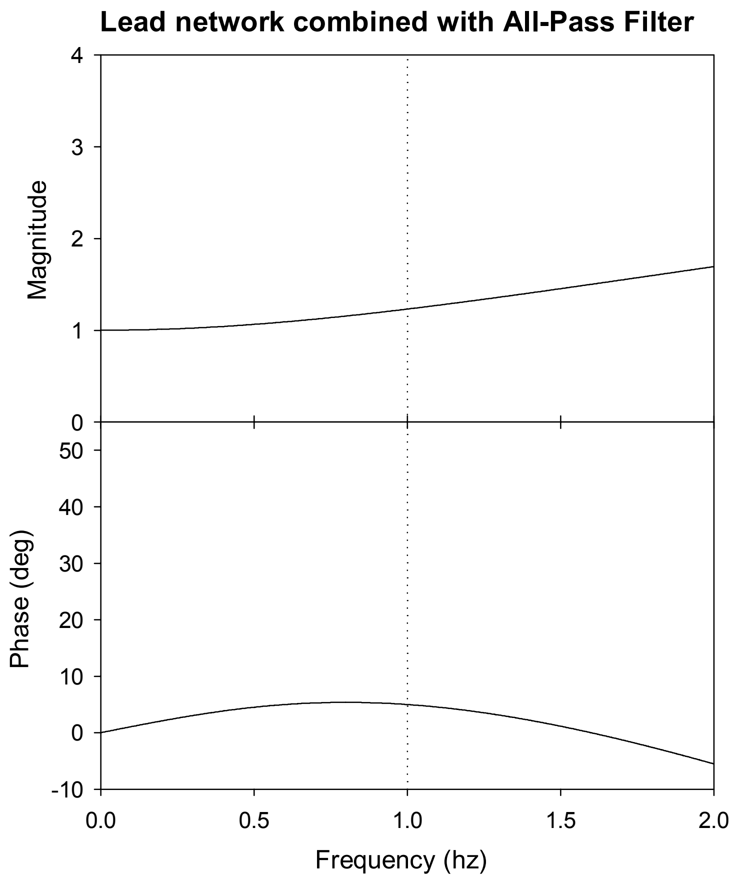


Figure B4
Magnitude and phase response of chosen lead network followed by all-pass filter.