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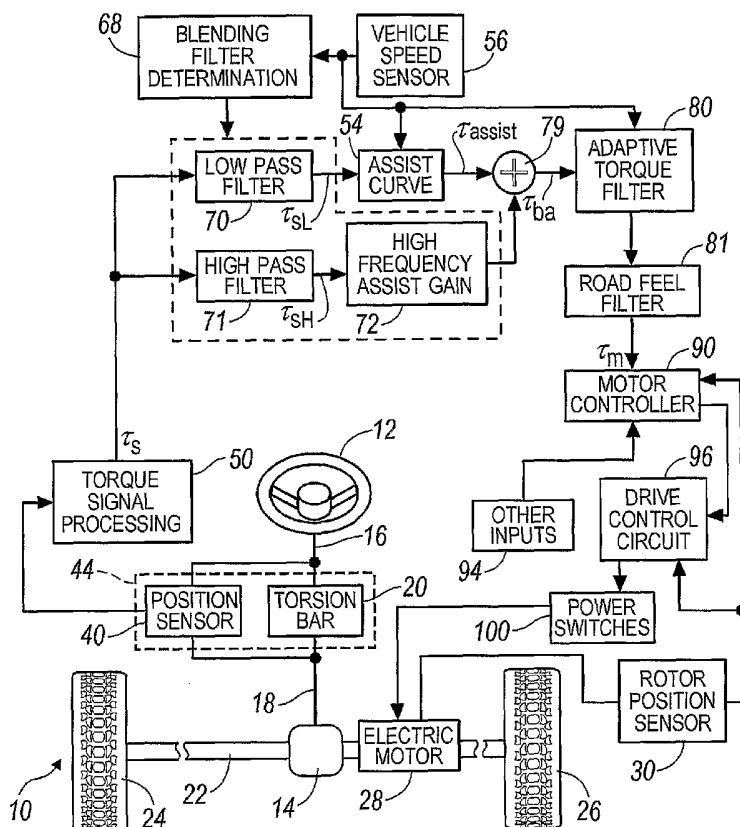
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(54) Title: METHOD AND APPARATUS FOR CONTROLLING AN ELECTRIC ASSIST STEERING SYSTEM USING AN ADAPTIVE BLENDING TORQUE FILTER AND ROAD FEEL FILTER



(57) Abstract: An apparatus is provided for controlling a steering assist system that includes a torque sensing system operatively connected to a vehicle hand wheel for providing a torque signal indicative of an applied steering torque. A blending filter connected to the torque sensing system provides a blended torque signal. An adaptive torque filter filters the blended torque signal for maintaining stability at all vehicle speeds. A road feel filter connected to the adaptive torque filter removes a lag-lead induced by an interaction of the adaptive torque filter and the blending filter at substantially zero gain. A steering assist device provides steering assist in response to a control signal. A controller provides the control signal to the steering assist device in response to a modified adaptive torque signal. The road feel filter filters the lag-lead from the adaptive torque signal for allowing road feel to be transmitted through the hand wheel at substantially zero gain.



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METHOD AND APPARATUS FOR
CONTROLLING AN ELECTRIC ASSIST STEERING SYSTEM USING
AN ADAPTIVE BLENDING TORQUE FILTER AND ROAD FEEL FILTER

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CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application serial
number 60/662,021, filed March 15, 2005, the disclosure of which is incorporated
10 herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

Not Applicable.

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BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

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The present invention is directed to an electric assist steering system and is
particularly directed to a method and apparatus for controlling an electric assist
steering system to improve steering feel.

DESCRIPTION OF THE RELATED ART

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Electric assist steering systems are well known in the art. Electric power
assist steering systems that utilize a rack and pinion gear set provide power assist by
using an electric motor to either (i) apply rotary force to a steering shaft connected to a
pinion gear, or (ii) apply linear force to a steering member having the rack teeth
30 thereon. The electric motor in such systems is typically controlled in response to (i) a
driver's applied torque to the vehicle steering wheel, and (ii) sensed vehicle speed.

In U.S. Pat. No. 3,983,953, an electric motor is coupled to the input steering shaft and energized in response to the torque applied to the steering wheel by the vehicle operator. The steering system includes a torque sensor and a vehicle speed sensor. A computer receives the output signals provided by both the torque and speed
5 sensors. The computer controls the amount of steering assist provided by the motor dependent upon both the applied steering torque and the sensed vehicle speed.

U.S. Pat. No. 4,415,054, to Drutchas (now U.S. Reissue Pat. No. 32,222,), assigned to TRW Inc., utilizes a D.C. electric assist motor driven through an "H-bridge" arrangement. The assist motor includes a rotatable armature encircling a
10 steering member. The steering member has a first portion with a thread convolution thereon and a second portion with straight cut rack teeth thereon. Rotation of the electric assist motor armature causes linear movement of the steering member through a ball-nut drivably connected to the thread convolution portion of the steering member. A torque sensing device is coupled to the steering column for sensing driver applied
15 torque to the steering wheel. The torque sensing device uses a magnetic Hall-effect sensor that senses relative rotation between the input and output shafts across a torsion bar. An electronic control unit ("ECU") monitors the signal from the torque sensing device and controls the electric assist motor in response thereto. A vehicle speed sensor provides a signal to the ECU indicative of the vehicle speed. The ECU controls
20 current through the electric assist motor in response to both the sensed vehicle speed and the sensed applied steering torque. The ECU decreases steering assist as vehicle speed increases. This is commonly referred to in the art as speed proportional steering.

U.S. Pat. No. 4,660,671, discloses an electric controlled steering system that is based on the Drutchas steering gear. In the arrangement shown in the '671 patent,
25 the D.C. motor is axially spaced from the ball-nut and is operatively connected thereto through a connection tube. The electronic controls includes a plurality of diagnostic features that monitor the operation of the steering system. If an error in the operation of the electric steering system is detected, the power assist system is disabled and steering reverts to an unassisted mode.

U.S. Pat. No. 4,794,997, to North, assigned to TRW Cam Gears Limited, discloses an electric assist steering system having an electric motor operatively connected to the rack through a ball nut. A vehicle speed sensor and an applied steering torque sensor are operatively connected to an ECU. The ECU controls electric
5 current through the motor as a function of both applied steering torque and sensed vehicle speed. The current is controlled by controlling the pulse-width-modulated ("PWM") signal applied to the motor. As the PWM increases, power assist increases. The ECU or computer is preprogrammed with discrete control curves that provide steering assist values (PWM values), also referred to as torque-out values, as a
10 function of applied steering torque, also referred to as torque-in values, for a plurality of predetermined discrete vehicle speed values. Each vehicle speed value has an associated torque-in vs. torque-out control curve.

U.S. Pat. No. 5,257,828, To Miller et al., discloses an electric assist steering system having yaw rate control. This system uses a variable reluctance motor to apply
15 steering assist to the rack member. The torque demand signal is modified as a function of the steering rate feedback.

Known electric assist steering systems have a dynamic performance characteristic, known as the system bandwidth, that varies as a function of vehicle speed. As the vehicle operator applies steering torque and rotates the steering wheel
20 back-and-forth, e.g., left-to-right-to-left, the electric assist motor is energized to provide steering assist commensurate with the steering inputs. How the steering system responds to a particular frequency of back-and-forth steering wheel movement is indicative of the system's dynamic performance.

The amount of local change at the electric assist motor divided by the
25 amount of local change in steering torque applied by the driver is the steering system gain. A time delay occurs from the time steering torque is applied to the steering wheel to the time the assist motor responds. This time delay is a function of the frequency at which the input command is applied. This is referred to as the system response time. The system gain is set to a predetermined value so as to have a short system response

time while still maintaining overall system stability. The system response time and system gain determines the system bandwidth.

The bandwidth in known steering systems varies as a function of vehicle speed. If dynamic steering frequency or the "frequency" of a transient response exceeds the system bandwidth at a particular vehicle speed, the steering feel becomes "sluggish" (felt as a "hesitation" when the steering wheel direction is changed) since the steering assist motor can not respond quick enough. Typically, steering system gain as well as system bandwidth decreases as the vehicle speed increases so that system hesitation or sluggishness becomes more noticeable as vehicle speed increases.

U.S. Pat. No. 5,504,403, which is incorporated by reference herein, discloses a torque sensing means operatively connected to a vehicle hand wheel for providing a torque signal indicative of applied steering torque. Blending filter means are connected to the torque sensing means for providing a blended filter torque signal having a first functional characteristic at torque frequencies less than a blending frequency and a second functional characteristic at torque frequencies greater than the blending frequency. The apparatus further includes steering assist means for providing steering assist in response to a control signal, and control means operatively connected to the blending filter means for providing said control signal to the steering assist means in response to the blended filter torque signal. The blending filtering means filters the torque signal so as to maintain a selectable system bandwidth during system operation.

Similarly, according to a later U.S. Pat. No. 5,704,446, which is incorporated by reference herein, a blending filter is provided for splitting the driver torque signal into a low frequency component in a high-frequency component. The low frequency component sets the high-frequency gain. This is so that the gain for the high-frequency component signal mirrors the effective gain of the low frequency components signal, whereby the high-frequency signal is close to but always slightly higher than the low-frequency signal. As this makes the high-frequency gain a function of the amplitude of the low-frequency torque signal component, a phase lag is

introduced into the high-frequency component above the blending frequency which itself could induce instability within the system.

U.S. Pat. No. 6,631,781, which is incorporated by reference herein, discloses a control means operatively connected to the blending filter means to provide a control signal to a steering assist means in response to a blended filtered torque signal whereby a high-frequency gain of the steering assist system is arranged to be low for on center operation of the hand wheel and relatively higher for off-center operation.

It is an object of the present invention to provide a blended filtering of the high and low-frequency torques present within the steering system and ensure stability and improved driver feel under high vehicle speeds and zero motor control gain conditions.

BRIEF SUMMARY OF THE INVENTION

The present invention has the advantage of providing a road feel filter in series with a blending torque filter and an adaptive torque filter for removing a lag-lead induced by the interaction of the blending torque filter and adaptive torque filter when the gain is substantially zero for allowing road feel to be transmitted through a steering wheel. At substantially high gains and substantially low gains, the road feel filter allow the blending torque filter and adaptive torque filter to function as if the road feel filter were not present thereby allowing a lag-lead and lead lag, respectively, to act upon the steering system.

In one aspect of the present invention, an apparatus is provided for controlling a steering assist system in response to a steering control signal, the steering system including a controller having gain. A torque sensing means is operatively connected to a vehicle hand wheel for providing a torque signal indicative of an applied steering torque. A blending filter means is connected to the torque sensing means for providing a blended filter torque signal having a first functional characteristic at a

torque frequency less than a blending frequency and a second functional characteristic at torque frequencies greater than the blending frequency. An adaptive filter means filters the blended filter torque signal for providing an adaptive filter torque signal for maintaining stability at substantially all vehicle speeds. A road feel filter means is
5 connected to the adaptive filter means for providing a modified adaptive filter torque signal for removing a lag-lead induced by an interaction of the adaptive filter means and the blending filter means at substantially zero gain. A steering assist means provides steering assist in response to a control signal. A control means is operatively connected to the road feel filter means for providing the control signal to the steering
10 assist means in response to the modified adaptive filter torque signal. The road feel filter means filters the lag-lead from an adaptive filter torque signal for allowing road feel to be transmitted through the hand wheel at substantially zero gain.

In yet another aspect of the present invention, an apparatus is provided for controlling a steering assist system in response to a steering control signal. The
15 apparatus includes a torque sensing system operatively connected to a vehicle hand wheel for providing a torque signal indicative of an applied steering torque. A blending filter connected to the torque sensing system provides a blended filter torque signal. An adaptive torque filter filters the blended filter torque signal for providing an adaptive filter torque signal for maintaining stability at all vehicle speeds. A road
20 feel filter connected to the adaptive torque filter for providing modified adaptive filter torque signal removes a lag-lead induced by an interaction of the adaptive torque filter and the blending filter at substantially zero gain. A steering assist device provides steering assist in response to a control signal. A controller having gain and operatively connected to the road feel filter provides the control signal to the steering assist device
25 in response to the modified adaptive filter torque signal. The road feel filter filters the lag-lead from the adaptive filter torque signal for allowing road feel to be transmitted through the hand wheel at substantially zero gain.

A method is provided for controlling a steering assist system which provides steering assist in response to a steering control signal, the steering assist system

includes a controller having gain. An applied steering torque is measured and a torque signal is provided indicative of the measured applied steering torque. A blended filter means is applied to the torque signal for producing a blended torque signal. An adaptive filter means is provided to the blended filter torque signal for producing an adaptive filter torque signal. A road feel filtering means is provided to the adaptive filter torque signal for removing lag-lead from the adaptive filtered torque signal for producing the steering control signal. Steering assist is provided in response to the steering control signal.

A method is provided for controlling a steering assist system which provides steering assist in response to a steering control signal. An applied steering torque is measured and a torque signal is provided indicative of the measured applied steering torque. A blended filter means is applied to the torque signal for producing a blended torque signal. An adaptive filter means is provided to the blended filter torque signal for producing a modified adaptive filter torque signal. A road feel filtering means is provided to the adaptive filter torque signal for removing lag-lead from the adaptive filtered torque signal for producing the steering control signal. Steering assist is provided in response to the steering control signal. The removal of the lag-lead allows road feel to be transmitted through a steer wheel.

A method is provided for controlling a steering assist system which provides steering assist in response to a steering control signal. An applied steering torque is measured and a torque signal is provided indicative of the measured applied steering torque. A blended filter means is applied to the applied torque signal for producing a blended torque signal. An adaptive filter means is provided to the blended filter torque signal for producing an adaptive filter torque signal. A road feel filtering means is provided to the adaptive filter torque signal for removing lag-lead from the adaptive filtered torque signal for producing the steering control signal. Steering assist is provided in response to the steering control signal. The road feel filter means cancels a low frequency pole of the adaptive filter means at substantially zero gain.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic block diagram illustrating a prior art power assist steering system.

Fig. 2 is a schematic drawing representation of the prior art linearized closed loop control system.

Fig. 3 is a graphical representation of torque-in vs. torque-out control curves that vary as a function of vehicle speed.

Fig. 4a and 4b are Bode plots of the prior art open loop system.

Fig. 5 is a block diagram of a transfer function for a steering system.

Fig. 6 is a modified block diagram of the transfer function shown in Fig. 5.

Fig. 7 is a modified block diagram of the transfer function shown in Fig. 6.

Fig. 8 is a modified block diagram of the transfer function shown in Fig. 7.

Fig. 9 is a modified block diagram of the transfer function shown in Fig. 8 according to a preferred embodiment of the present invention.

Fig. 10 shows a plurality of gain plots of the transfer function.

Fig. 11 is a schematic block diagram illustrating a power assist steering system according to a preferred embodiment of the present invention.

Fig. 12 is a block diagram illustrating a road feel filter according to a preferred embodiment of the present invention.

Figs. 13a and 13b show comparison gain plots of the controller with and without the road feel filter according to a preferred embodiment of the present invention.

Figs. 14a and 14b show comparison bode plots of disturbance gain and phase angles.

Figs. 15a-c show assist and input torque curve plots according to a preferred embodiment of the present invention.

Figs. 16a-d show comparative time domain plots for a first set of input torque commands at a park condition.

Figs. 17a-d show comparative time domain plots for a second set of input torque commands at the park condition.

5 Figs. 18a-d show comparative time domain plots for a first set of input torque commands for a respective speed.

Figs. 19a-d show comparative time domain plots for a second set of input torque commands for the respective speeds.

Fig. 20a and Fig. 20b show bode plots for a hand wheel free system.

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DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Fig. 1 illustrates a power assist steering system **10** of the type described in U.S. Patent No. 5,504,403. The power assist steering system **10** includes a steering wheel **12** operatively connected to a pinion gear **14**. Specifically, the vehicle steering wheel **12** is connected to an input shaft **16** and the pinion gear **14** is connected to an output shaft **18**. The input shaft **16** is operatively coupled to the output shaft **18** through a torsion bar **20**.

The torsion bar **20** twists in response to applied steering torque thereby permitting relative rotation between the input shaft **16** and the output shaft **18**. Stops, not shown, limit the amount of such relative rotation between the input and output shafts in a manner known in the art. The torsion bar **20** has a spring constant referred to herein as K_t . In accordance with a preferred embodiment, the spring constant $K_t = 20$ in-lb/deg. The amount of relative rotation between the input shaft **16** and the output shaft **18** in response to applied steering torque is functionally related to the spring constant of the torsion bar.

As is well known in the art, the pinion gear **14** has helical teeth which are meshingly engaged with straight cut teeth on a rack or linear steering member **22**. The pinion gear **14** in combination with the straight cut gear teeth on the rack member **22** form a rack and pinion gear set. The rack is steerably coupled to the vehicle's steerable

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wheels **24, 26** with steering linkage in a known manner. When the steering wheel **12** is turned, the rack and pinion gear set converts the rotary motion of the steering wheel **12** into linear motion of the rack **22**. When the rack moves linearly, the steerable wheels **24, 26** pivot about their associated steering axes and the vehicle is steered.

5 An electric assist motor **28** is drivingly connected to the rack **22** through a ball-nut drive arrangement also known in the art. Such an arrangement is fully described in U.S. Pat. No. 5,257,828, to Miller et al., assigned to TRW Inc., which is hereby fully incorporated herein by reference. When the electric motor **28** is energized, it provides power assist steering so as to aid in the rotation of the vehicle steering wheel **12** by the
10 vehicle operator.

 In accordance with a preferred embodiment of the present invention, the electric assist motor **28** is a variable reluctance motor. A variable reluctance motor is desirable for use in an electric assist steering system because of its small size, low friction, and its high torque-to-inertia ratio. The motor **28**, in accordance with a
15 preferred embodiment of the present invention, includes eight stator poles and six rotor poles. The stator poles are arranged so as to be energized in pairs designated Aa, Bb, Cc, and Dd.

 The operation of a variable reluctance motor and its principle of operation are well known in the art. Basically, the stator poles are energized in pairs. The rotor
20 moves so as to minimize the reluctance between the stator poles and the rotor poles. Minimum reluctance occurs when a pair of rotor poles are aligned with the energized stator poles. Once minimum reluctance is achieved, i.e., when the rotor poles align with the energized stator coils, those energized stator coils are de-energized and an adjacent pair of stator coils are energized.

25 The direction of motor rotation is controlled by the sequence in which the stator coils are energized. The torque produced by the motor is controlled by the current through the stator coils. When the motor is energized, the rotor turns which, in turn, rotates the nut portion of the ball-nut drive arrangement. When the nut rotates, the

balls transfer a linear force to the rack. The direction of rack movement is dependent upon the direction of rotation of the motor.

A rotor position sensor **30** is operatively connected to the motor rotor and to the motor housing. The above-incorporated '828 patent shows and describes such a rotor position sensor **30** in detail, the description of which being hereby fully incorporated herein by reference. One of the functions of the rotor position sensor **30** is to provide an electrical signal indicative of the position of the rotor relative to the motor stator. For proper operation of the variable reluctance motor, including direction of rotation and applied torque, it is necessary to know the position of the rotor relative to the stator.

A position sensor **40** is operatively connected across the input shaft **16** and the output shaft **18** and provides an electrical signal having a value indicative of the relative rotational position or relative angular orientation between the input shaft **16** and the output shaft **18**. The position sensor **40** in combination with the torsion bar **20** form a torque sensor **44**. The steering wheel **12** is rotated by the driver during a steering maneuver through an angle Θ_{HW} . The relative angle between the input shaft **16** and the output shaft **18** as a result of applied input torque is referred to herein as Θ_p . Taking the spring constant K_t of the torsion bar **20** into account, the electrical signal from the sensor **40** is also indicative of the applied steering torque referred to herein as τ_s .

The output of the torque sensor **44** is connected to a torque signal processing circuit **50**. The processing circuit **50** monitors the angle Θ_p and, "knowing" what the spring constant K_t of the torsion bar **20** provides an electric signal indicative of the applied steering torque τ_s .

The torque sensor signal is passed through a pair of blending filters. The two blending filters are constructed such that the first is a low pass filter **70** and the second is a high pass filter **71**. The filters are designed such that summation of the two filters is identically one for all frequencies. The low pass filter **70** allows all of the signal τ_s with frequency content below some blending frequency ω_b to pass through while

rejecting all high frequency data. The high pass filter allows all of the signal τ_s with frequency content above some blending frequency ω_b to pass through while rejecting all low frequency data. The blending filter frequency ω_b is a function of vehicle speed and is determined by the blending filter determination circuit 68. The determination of ω_b may be accomplished using a look-up table in a microcomputer or may be accomplished using an actual calculation in accordance with a desired control function. The low pass torque sensor output signal τ_{sL} is connected to an assist curve circuit 54.

The assist curve circuit 54 is preferably a look-up table that provides a desired torque assist signal τ_{Assist} having a value functionally related to the low passed applied steering torque τ_{sL} and sensed vehicle speed. A vehicle speed sensor 56 is also operatively connected to the assist curve circuit 54. The assist curve function may be accomplished using a look-up table in a microcomputer or may be accomplished using an actual calculation in accordance with a desired control function.

As is well known in the art, the amount of power assist desired for a vehicle steering system decreases as vehicle speed increases. Therefore, to maintain a proper or desirable feel to steering maneuvers, it is desirable to decrease the amount of steering power assist as the vehicle speed increases. This is referred to in the art as speed proportional steering.

Fig. 3 shows output torque τ_{assist} verses applied input torque τ_{sH} for various vehicle speeds as illustrated in the '403 patent. Line 60 is the torque-in vs. torque-out values for what is referred to in the art as dry surface parking. Line 66 is the torque-in vs. torque-out values for high vehicle speeds. Line 69 shows the direction of how values change as vehicle speed increases. Generally, the value of the output from the assist curve circuit 54 is referred to as τ_{assist} .

Preferably, the τ_{assist} value is determined according to:

$$\tau_{assist} = S_p \times (LS) + (1 - S_p) \times (HS) \quad (1)$$

where LS is the set of lowest speed τ_{assist} values for a given low passed input torque, HS is the set of highest speed τ_{assist} values for a given low passed input torque, and S_p is a speed proportional term that varies between 1 at parking speed and 0 at a predetermined high speed. This provides a smooth interpolation of values as vehicle speed increases. This determination of the τ_{assist} value is fully described in U.S. Patent No. 5,473,231, to McLaughlin et al., assigned to TRW, and is hereby fully incorporated herein by reference.

The high passed torque sensor signal τ_{sH} is connected to a high frequency assist gain circuit 72. The high frequency assist gain circuit 72 multiplies the high passed torque sensor signal τ_{sH} by a predetermined gain S_{c1} that is a function related to vehicle speed. The determination of S_{c1} may be accomplished using a look-up table in a microcomputer or may be accomplished using an actual calculation in accordance with a desired control function. Modification of the high frequency assist gain S_{c1} allows the bandwidth of the steering system to be modified.

The outputs of the assist curve circuit 54 and the high frequency assist gain circuit 72 are summed in a summing circuit 79. The output of the summing circuit 79 is referred to as τ_{ba} (i.e., blended filter torque signal) and is coupled to the adaptive filter circuit 80. The adaptive filter circuit 80 filters the input blended filter torque signal τ_{ba} . The filter is adaptive in that its poles and zeros are allowed to change as the vehicle speed changes so as to provide an optimal control system. The combination of this filtering is referred to as adaptive blending filtering and results in an adaptive filtered torque signal τ_{m} , which is referred to as the torque demand signal. The torque demand signal is connected to a motor controller 90. The motor controller 90 controls energization of the motor 28 in response to the torque demand signal τ_{m} . The rotor position sensor 30 is also connected to the motor controller 90. The motor controller 90 controls steering damping in response to sensed rotor speed, as is fully described in the above-incorporated '828 patent. Other inputs 94 are connected to the motor controller 90. These other inputs 94 include an ECU temperature sensor, soft-start

circuitry, etc. These other inputs are also fully described in the above-incorporated '828 patent.

The output of the motor controller **90** is connected to a drive control circuit **96**. The drive control circuit is controllably connected to a plurality of power switches **100** to control the application of electrical energy to the electric assist motor **28**. The output from the rotor position sensor **30** is also connected to the drive control circuit **96**. As mentioned above, control of a variable reluctance motor requires that the relative position between the rotor and the stator be known.

Fig. 2 illustrates a linearized closed loop control system as described in the '403 patent. The linearized closed loop control system is required because it is used to design the blending filter and adaptive filter for the steering system. Rotation of the hand wheel **12** results in an angular displacement of Θ_{HW} on the steering wheel side of the torsion bar position sensor. This angular displacement is differenced with the resultant angular displacement of the output shaft **18** after it is driven in rotation by the electric assist motor by an angle Θ_m through the gearing ratio **110** represented by r_m/r_p where r_m is the effective radius of the motor ball nut and r_p is the effective radius of the pinion. In one embodiment of the present invention, the values are $r_m=0.05$ in. and $r_p=0.31$ in. One radian of rotation of the ball nut produces r_m inches of travel of the rack. Similarly, one radian of rotation of the pinion produces r_p inches of travel of the rack. The resultant angular displacement Θ_p times the spring constant K_t gives the torque signal τ_s . In the closed loop arrangement, switch **53** connects the output τ_s to the low pass/high pass filter circuits.

The torque signal τ_s is passed through the low pass filter **70** resulting in the low passed assist torque τ_{sL} . The high passed assist torque τ_{sH} is determined by subtracting the low frequency assist torque from the torque signal τ_s . The reason that τ_{sH} can be determined in this way is discussed below.

The continuous domain blending filters are chosen such that the sum of the low pass filter $G_L(S)$ and the high pass filter $G_H(S)$ is always equal to one:

$$G_L(S) + G_H(S) = 1 \quad (2)$$

The low pass filter is chosen to be a first order filter with a pole at ω_b . The high pass filter is uniquely defined by the above constraint that the sum of the two filters must be one. Therefore, the low and high pass filters are:

$$G_L(S) = \frac{\omega_b}{S + \omega_b} \quad (3)$$

$$G_H(S) = \frac{S}{S + \omega_b} \quad (4)$$

When realizing a set of blending filters in a digital computer, those skilled in the art will appreciate that it is not necessary to construct separate high and low pass filter stages. Rather, the input to the blending filters τ_s is passed through the low pass filter resulting in the signal τ_{sL} . The high passed signal is the original input torque minus the low passed portion:

$$\tau_{sH} = \tau_s - \tau_{sL} \quad (5)$$

This can be thought of equivalently as determining the low frequency portion of the signal and simply subtracting it out of the original signal. The result is a signal with only high frequency information. Alternatively, one can use higher order blending filters. However, the complexity of the filter computations increases with filter order in a digital computer. The use of first order filters is preferred.

The low passed torsion bar torque signal τ_{sL} is connected to the assist curve circuit **54**. Referring again to Fig. 2, the linearized control system includes an assist curve circuit **54** designated as a gain S_c . The gain S_c is the local derivative of the assist function with respect to the input torque evaluated at some low passed input torque and speed.

$$S_c = \frac{\delta \tau_{assist}}{\delta \tau_{sL}} \quad (6)$$

The gain S_c represents how much incremental assist τ_{Assist} is provided for an incremental change in low passed input torque τ_{sL} about some nominal low passed input torque and vehicle speed. For example, the low speed assist curve **60** in FIG. 3 has a shallow slope as the torque is increased out of the deadband and a steeper slope at a high input torque of 25 in-lb. Therefore, the gain S_c is small near the deadband and increases as the torque increases away from the deadband. The difference in slope is even greater for the high speed assist curve **66** of FIG. 3. For a low passed input torque of 10 in-lb., a large change in low passed input torque is required to effect even small changes in assist torque. Therefore, S_c is small. For an input torque of 50 in-lb., a small change in low passed input torque produces a large change in assist torque. For the high speed assist curve, S_c is very small near the deadband and very large at 50 in-lb. of low passed input torque.

In the linearized realization of the steering system, the low passed torque τ_{sL} is multiplied by the local gain of the assist curve to determine τ_{assist} . The low passed assist value τ_{assist} is summed with the high passed assist value. The high passed assist value is determined by multiplying the high passed torque sensor signal τ_{sH} times the high frequency assist gain S_{c1} . The blended assist is:

$$\tau_{ba} = \tau_{assist} + ((S_{c1}) \times (\tau_{sH})) \quad (7)$$

The pole of the blending filter ω_b and the high frequency assist gain S_{c1} are computed as functions of speed in circuits **83** and **74** respectively. The determination of ω_b and S_{c1} may be accomplished using a look-up table in a microcomputer or may be accomplished using actual calculations. The circuits **83** and **74** in the linearized closed loop transfer function of Fig. 2 form the blending filter determination circuit **68** of Fig. 1. The blended assist is connected to the adaptive torque filter G_f . The adaptive torque

filter allows the vehicle steering system to adapt to changes in the dynamics of the system that occur as the vehicle speed changes.

The output from the adaptive torque filter **80** is a torque demand signal τ_m . In the closed loop arrangement, switch **55** connects τ_m to the summing circuit **116**. The motor provides a torque assist which is summed with the manual assist transmitted through the pinion shaft producing a total torque τ_r on the rack. This torque is applied to the transfer function G_m which represents the dynamics of the steering gear. The input to G_m is the total torque applied to the motor via the rack and ball nut from the input pinion and the motor and the output is the motor rotation angle. The transfer function G_m is referenced directly to the motor so that the input is the total torque on the motor and the output is motor angle. The restoring force applied by the tires on the rack is modeled as a spring force which is not shown because it is internal to G_m .

Three key features of the blending filter topology should be appreciated. If the local assist gain S_c is equal to the high frequency assist gain S_{c1} , the blended assist torque τ_{ba} is identically equal to the measured torque τ_s times the gain S_{c1} . This results from the fact that the sum of the low passed and high passed filters is equal to one. If the outputs of the two filters are multiplied by the same gain, the sum of the two outputs will just be the gain times the inputs. This characteristic of the blending filter topology is used when designing a controller for the steering system. Also, the low frequency or DC gain of the filter stage between the measured torsion bar torque τ_s and the blended assist torque τ_{ba} is set by the local gain of the assist curve S_c . This occurs because the output of the high pass filter stage **71** is zero for low frequency inputs so that all of the torque sensor signals pass through the low pass filter. Since the assist curve is a nonlinear element providing different incremental levels of assist for the same increment change in input torque, i.e., S_c changes in response to input torque and vehicle speed, the DC gain of the steering system is entirely selectable and tunable by changing the assist curve. Furthermore, the high frequency gain of the filter stage between the measured torsion bar torque τ_s and the blended assist torque τ_{ba} is always S_{c1} . At high frequency, the output of the low pass stage of the blending filter is zero so

that all of the torque sensor signal passes through the high pass filter stage. Since the high frequency gain of the high pass stage is S_{c1} , the gain between τ_s and τ_{ba} is S_{c1} .

The blending filters have the unique characteristic of responding like a linear system to a high frequency input signal and like a nonlinear system to a low frequency input signal. For example, if the steering torque signal changes rapidly, as might occur due to torque ripple from the VR electric assist motor **28**, the driver inputting a rapid input torque, or the wheels responding to a sudden bump in the road, the high frequency inputs are rejected by the low pass filter **70** and the response of the system would be dominated by the high pass portion of the loop under these steering conditions. However, if the input to the system is smooth and slow, then the high pass filter rejects the low frequency input and the system response is dominated by the non-linear assist curve. The system is both responsive to fast inputs and can achieve any feel or assist curve for low frequency inputs.

The filter G_f , in accordance with a preferred embodiment, is a constant filter that is not a function of vehicle speed. The present invention contemplates that this filter G_f would be an adaptive filter that adapts as a function of vehicle speed. It is designed by measuring the open loop transfer function G_p as a function of speed and designing a filter that meets stability and performance specifications for all speeds. In accordance with one embodiment of the present invention, the open loop transfer functions are designed to have the same bandwidth for all speeds. The present invention is not, however, so limited, i.e., the steering system bandwidth can vary as a function of vehicle speed.

One skilled in the art will appreciate that controller design requires that the system dynamics must be identified prior to designing of the controller. Specifically, it is necessary to identify dynamics of the open loop transfer function. The open loop transfer function, for the purposes of this application, occurs when the motor command τ_m is used as the input and the measured torque sensor signal τ_s is the output. To establish such an open loop system, switches **53** and **55** are switched so as to remove the assist curves, blending filters, and the adaptive torque filter from the

system. The transfer function is measured on a vehicle for a particular system using a signal analyzer to command the motor at various input frequencies and measuring the output of the torque sensor with the hand wheel held in a fixed position. This measured transfer function is designated as G_p and an example of such is shown in FIGS. 4a and 4b. (The actual values are dependent upon the particular vehicle application.) This measured open loop transfer function is then used to design the adaptive torque filter **80** so that the steering torque loop has a desired stability and performance characteristics.

One skilled in the art will appreciate that the open loop transfer function G_p can also be determined by creating a linear model of the dynamics of the rack, tires, motor, ball nut, electronics, etc. If G_p is determined from an analytical model, then all of the dynamics involved in converting a torque command at the motor to a measured torsion bar signal must be included in the model. It is preferred to measure this transfer function directly as analytical models rarely match real world phenomenon exactly especially with regard to the phase angle of the transfer function.

Bode plots as shown in Fig. 4a and 4b were generated with the vehicle stationary on a dry, flat surface. This is commonly referred to as "dry park." The hand wheel was locked. Any controller designed using this measured transfer function will work well at dry park. As the vehicle speed increases, the controller may not function as desired since the open loop transfer function may change. The open loop transfer function is preferably measured at several different vehicle speeds and the filters are designed for each of these speeds. The vehicle speed is measured in real time and the corresponding filter is used in the control determination. The control system's torque filter "adapts" to steering dynamic changes as a function of vehicle speed. To measure the open loop transfer function as a function of vehicle speed is difficult.

Alternatively, the open loop transfer function at dry park can be measured and used to develop a model that correlates well to the measured data. The model can then be used to determine the open loop transfer function at higher vehicle speeds.

Although the preferred embodiment of the present invention allows the adaptive filter to change as the dynamics of the steering system change, only the dry park condition transfer function as shown in the Bode plots of Figs. 4a and 4b is used for illustrating the design process. Once the steps required for dry park are understood,
 5 torque filters can be designed for different vehicle speeds.

Torque filter design is performed using classical open loop techniques. The open loop steering system transfer function G_p is measured and is shown in Figs. 4a and 4b. The open loop transfer function that must be stabilized includes not only G_p , but also any gain due to the assist curve. In one embodiment of the '403 patent, the
 10 maximum assist gain $(S_c)_{\max}$ is 5.

If a gain of 5 (or 14 db) is added to the gain portion of the Bode plot of FIGS. 4a and 4b, the system will have insufficient stability margins. Therefore a filter is added to the open loop system to achieve desired performance and stability objectives which is represented as follows:

$$G_f = \frac{(S + 40)^2}{(S + 4)x(S + 400)} \quad (8)$$

The torque filter G_f is a lag-lead type filter that is designed to provide a system with adequate performance and stability margins at a maximum steering system gain of 5.

20 However, the blending filters when utilized in combination with the torque filter G_f has the undesirable property of inducing a lag/lead filter at high vehicle speeds under zero assist gain conditions. This implicit filter (i.e., blending filter) negatively impacts "road feel" by inducing lag in the electric assist motor which reduces the effects of "road feel" inputs felt through the steering wheel when the gain
 25 is zero. Such "road feel" or responsiveness of the steering wheel to variations in the road surface as felt through the steering wheel is desired by drivers of the vehicle. A good "road feel" gives a perception of better vehicle control when traveling at a zero degree steering wheel angle over a rough or bumpy surface, for example.

The following Figs. 5-10 illustrate the dynamics and theoretical limits for “road feel.” It will be shown that the maximum gain for “road feel” is equal to the gain of the open loop system. Eqs. 5-10 illustrate how the blending filters and adaptive torque filter implicitly induce a lag in the steering system at zero assist gain which inhibits “road feel.”

A general block diagram of a preferred transfer function for a steering system is shown in Figs. 5. The following nomenclature is used in the description and figures which follow:

- 10 r_m = Effective ballnut lead,
- r_p = Effective pinion C-factor,
- $r_{mp} = r_m/r_p$,
- K_T = Torsion bar stiffness (or transfer function),
- G_c = Controller transfer function (torque filter, blending filter, assist, etc.,
- 15 G_m = Plant Transfer function (rack/tire inertia, rack friction, tire stiffness),
- τ_m = motor command torque,
- τ_d = disturbance torque.

The transfer function **101** as illustrated in Fig. 5 can be can be rearranged as shown in Fig. 6 which illustrates the relationship from the motor command input signal τ_m to the sensed torque output τ_s **104**. A disturbance torque τ_d **106** shown as an input signal is summed with the motor command input signal τ_m **102** and the gear ratio feedback signal r_m/r_p **107**. The disturbance torque τ_d **106** is produced from either the electric assist motor or the road if an assumption of zero gear compliance is observed.

25 A transfer function **103** as illustrated in Fig. 6 can be simplified and represented by a disturbance rejection transfer function **105** as shown in Fig. 7. The disturbance rejection transfer function **105** of Fig. 7 is modified by the addition of the controller transfer function G_c as illustrated in Fig. 8. The block diagram as shown in Fig. 8 is further modified as illustrated in Fig. 9. A sensitivity transfer function **108** as shown

in Fig. 9 satisfies the Bode Sensitivity Integral Theorem which states that for a system with no right half plane poles and two more poles than zeros, if $S(j\omega)$ is defined as,

$$S(j\omega) = \frac{1}{1 + G_c G_p}, \quad (9)$$

5

then

$$\int_0^{\infty} \log|S(j\omega)| d\omega = 0. \quad (10)$$

$S(j\omega)$ is equal to the sensitivity transfer function **108** as shown in Fig. 9. Eq. (10)

10 indicates that energy that is rejected in the low frequency shows up in the high frequency, and conversely, energy that is present in the low frequency is reduced in the high frequency. If the plant is fixed, then the motor controller simply moves the energy around. However, any control action that uses motor angle or its derivatives as an input can modify G_p directly, (e.g. rack damping). The dc gain of G_p is not
15 modified by the control actions, but rather the control actions modify the pole location and the damping of the poles of G_p .

For a fixed hand wheel case, G_p is a second order system. When the motor controller is outputting substantially zero gain (i.e., $G_c=0$), the gain of the transfer function **108** is equal to 1 and the maximum gain of the disturbance rejection transfer
20 function **105** is G_p . As the controller gain G_c increases, the gain of the transfer function **108** becomes less than 1 because the phase of the open loop system is within 90 degrees of zero.

Fig. 10 illustrates the gain of the sensitivity transfer function **108** and the phase angle for an open loop plant. If the phase angle is below 90 degrees, the gain of $S(j\omega)$
25 is less than 1 for all gains of $G_c G_p$. As the gain of $G_c G_p$ increases, the gain of $S(j\omega)$ can increase above 1 only for phase angles greater than 90 degrees. Below the natural frequency of the fixed case, the phase is below 90 degrees because the system is second order. The addition of lead/lag extends the 90 degree frequency higher. So in

general, adding gain via the control function reduces the gain of $S(j\omega)$ while also reducing the gain of the disturbance rejection transfer function and negatively impacting road feel.

Since the gain of $S(j\omega)$ is less than 1 below a frequency higher than the natural frequency of the fixed plant, the maximum gain of the disturbance rejection transfer function **105** in this region is G_p . In summary, the maximum gain of the disturbance rejection transfer function **105** is G_p so long as the phase angle of $G_c G_p < 90^\circ$. Increasing "road feel" below the natural frequency of the steering system is only possible by increasing the dc gain of the steering system which is accomplished by altering the pinion ratio. Increasing the natural frequency of the steering system by either increasing the stiffness or decreasing the inertia will only extend the frequency where maximum disturbance rejection is achievable but will not increase the gain. For example, if the inertia is reduced by 50% then the natural frequency of the steering system increases by 25%. So if the natural frequency of G_p is 8Hz, the new natural frequency will be 10Hz. This modification possibly improves the frequency content of the "road feel" information at the hand wheel, but will not improve the overall magnitude of this "road feel" information below 8Hz. In fact, a lower inertia system will require more control to reduce the natural damping and may in fact have poorer "road feel."

As a result, minimizing controller gain is essential to improving "road feel" at zero gain conditions. At zero gain, the maximum limit is the open loop hand wheel fixed transfer function. The gain is not minimized in the blending filter implementation previously described.

The blending filter G_{blend} and the adaptive torque filter G_f are in series as a function of G_c as represented by the following equation:

$$G_c = G_{blend} G_f, \quad (11)$$

where

$$G_{\text{blend}} = K_A \frac{a}{s+a} + K_{\text{max}} \frac{s}{s+a}, \text{ and} \quad (12)$$

$$5 \quad G_f = \frac{(s+\alpha)(s+\alpha)}{(s+\frac{\alpha}{\beta})(s+\alpha\beta)}. \quad (13)$$

The following nomenclature is used in the description and figures which follows:

K_A = Assist Gain

10 K_{max} = High Frequency Gain

A = Blending Frequency

α = Biquad Zero (nominally 40 rad/sec)

β = Biquad separation (nominally 10)

15 The biquad is assumed symmetric for this analysis. Eq. (12) and (13) can be substituted into eq. (3) yielding,

$$G_c = \left(K_A \frac{a}{s+a} + K_{\text{max}} \frac{s}{s+a} \right) \left(\frac{(s+\alpha)(s+\alpha)}{(s+\frac{\alpha}{\beta})(s+\alpha\beta)} \right), \quad (14)$$

or,

20

$$G_c = K_{\text{max}} \left(\frac{s+a \left(\frac{K_A}{K_{\text{max}}} \right)}{s+a} \right) \left(\frac{(s+\alpha)(s+\alpha)}{(s+\frac{\alpha}{\beta})(s+\alpha\beta)} \right). \quad (15)$$

Rearranging the poles yields,

$$G_c = K_{\max} \left(\frac{s + \alpha \left(\frac{K_A}{K_{\max}} \right)}{s + \alpha\beta} \right) \left(\frac{s + \alpha}{s + \frac{\alpha}{\beta}} \right) \left(\frac{s + \alpha}{s + a} \right). \quad (16)$$

In general, the values of "a" and "α" are very close so the gain of (s+α)/(s+a) is

- 5 approximately equal to 1. This term can be neglected, but it will be maintained for illustrating the following analysis. Various gains including high gains (e.g., $G_c > 20$), low gains (e.g., $G_c < 2$), and zero gain (e.g., $G_c = 0$) are shown and analyzed in Table 1. Results utilizing $\alpha=a=40$ and $\beta=10$ and are also shown.

10 Table 1: Overall Control Action of Blending and Adaptive Torque Filter for Three Gains

#	Gain K_A	Generalized Filter	Belt Filter	Result
1	High Gain $K_A = K_{\max}$	$K_A \left(\frac{s + \alpha}{s + \alpha\beta} \right) \left(\frac{s + \alpha}{s + \frac{\alpha}{\beta}} \right) \left(\frac{s + \alpha}{s + a} \right)$	$K_A \left(\frac{s + 40}{s + 400} \right) \left(\frac{s + 40}{s + 4} \right)$	Lag/Lead
2	Low Gain $K_A = \frac{K_{\max}}{\beta}$	$K_{\max} \left(\frac{s + \alpha}{s + \alpha\beta} \right) \left(\frac{s + \alpha}{s + a} \right)$	$K_{\max} \left(\frac{s + 40}{s + 400} \right)$	Lead
3	Zero Gain $K_A = 0$	$K_{\max} \left(\frac{s}{s + \alpha\beta} \right) \left(\frac{s + \alpha}{s + \frac{\alpha}{\beta}} \right) \left(\frac{s + \alpha}{s + a} \right)$	$K_{\max} \left(\frac{s}{s + 400} \right) \left(\frac{s + 40}{s + 4} \right)$	Pseudo-Differentiator with lag/lead

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At high gain, it is assumed that $K_A = K_{\max}$. The resulting control is a lag/lead control strategy that is required to stabilize the system with sufficient stability margin as it is shown that the zero of the blending filter moves towards α . At low gain, the zero of blending filter cancels a pole (i.e., 4 rad/sec pole) of the torque filter G_f . The resulting control is lead/lag control strategy that is useful for preventing the motor from interfering with the driver inputs.

At zero gain, the zero of the blending filter moves to the origin. A low frequency pole of the torque filter is present at $\tilde{\alpha}/\beta$ because it is no longer cancelled by a zero of the blending filter G_{Blend} . The resulting control is a pseudo-differentiator (i.e., a differentiating filter below 400 rad/sec) and a lag/lead filter. At zero gain, the lag/lead adds no value as it does not improve the stability. In addition, the lead/lag adds gain in the controller which reduces the maximum possible response of the torque sensor to disturbance inputs. This inhibits “road feel” at zero gain. Alternatively, minimal gain in the controller would allow the disturbance rejection transfer function to approach the theoretical limit which would be optimal in allowing disturbance inputs to be felt in the steering wheel. Removing the lag/lead at zero gain would therefore be desirable.

A preferred embodiment for deterring the blending filter and torque filter from inhibiting “road feel” while the gain is zero includes inserting an additional “road feel” filter in series with the blending and torque filter.

Fig. 11 illustrates the addition of a road feel filter G_{FR} **81**. The road feel filter G_{FR} **81** is an additional first order filter that improves the on-center feel and “road feel”. Flick response and hesitation are also improved.

The additional road feel filter G_{RF} as shown in Fig. 11 is placed series with torque filter G_c and blending filter G_{Blend} for removing the lag/lead induced by the

interaction of the blending filter and the torque filter at substantially zero gain. The resulting equation is as follows:

$$G_c = \left(K_A \frac{a}{s+a} + K_{\max} \frac{s}{s+a} \right) \left(\frac{(s+\alpha)(s+\alpha)}{(s+\frac{\alpha}{\beta})(s+\alpha\beta)} \right) G_{RF} \quad (17)$$

5 or,

$$G_c = \left(K_A \frac{a}{s+a} + K_{\max} \frac{s}{s+a} \right) \left(\frac{(s+\alpha)(s+\alpha)}{(s+\frac{\alpha}{\beta})(s+\alpha\beta)} \right) \left(\frac{(s+\frac{\alpha}{\beta})}{s+\alpha} (1-K_{RF}) + K_{RF} \right) \quad (18)$$

where the road feel filter G_{RF} is,

10

$$G_{RF} = \left(\frac{(s+\frac{\alpha}{\beta})}{s+\alpha} (1-K_{RF}) + K_{RF} \right), \quad (19)$$

where K_{RF} is defined as:

$$15 \quad K_{RF} = \begin{cases} \frac{\tau_{\text{assist}}}{\tau_o}, & |\tau_{\text{assist}}| < \tau_o \\ 1, & |\tau_{\text{assist}}| \geq \tau_o \end{cases}. \quad (20)$$

At zero assist gain, $K_{RF}=0$. For $K_A=0$ and $K_{RF}=0$, eq. (10) is represented as,

$$G_c = \left(K_{\max} \frac{s}{s+a} \right) \left(\frac{(s+\alpha)(s+\alpha)}{(s+\frac{\alpha}{\beta})(s+\alpha\beta)} \right) \left(\frac{(s+\frac{\alpha}{\beta})}{s+\alpha} \right) = K_{\max} \frac{s}{s+\alpha\beta} \left(\frac{(s+\alpha)}{(s+a)} \right) \quad (21)$$

It is shown that the lag/lead is cancelled out by the road feel filter. Furthermore, if $a = \alpha$, the control is simply derivative. This produces minimum gain from the

5 controller function. If τ_{assist} increases above τ_o , then $K_{\text{RF}}=1$ and the road feel filter G_{RF} disappears and the blending filter functions as if G_{RF} were not present.

In summary, at high and low gains the road feel filter G_{FR} allows G_{Blend} and G_f to function as if the road feel filter G_{FR} was not present. At zero gain, the road feel filter G_{FR} cancels out the lag/lead thereby producing modified adaptive filter torque
10 signal with a minimum gain which allows “road feel” to be felt through the steering wheel.

Assuming $a=40$ and $\beta=10$, the road feel filter G_{FR} using these values is shown as,

$$15 \quad G_{\text{RF}} = \left(\frac{(s+\frac{\alpha}{\beta})}{s+\alpha} (1-K_{\text{RF}}) + K_{\text{RF}} \right) = \left(\frac{(s+4)}{(s+40)} (1-K_{\text{RF}}) + K_{\text{RF}} \right) \quad (22)$$

The lead/lag filter $(s+4)/(s+40)$ is realized as,

$$G_{\text{RF}} = \left(\frac{(s+4)}{(s+40)} (1-K_{\text{RF}}) + K_{\text{RF}} \right) = \left(\frac{s}{s+40} + \frac{40}{s+40} \left(\frac{1}{10} \right) \right) (1-K_{\text{RF}}) + K_{\text{RF}} \quad (23)$$

20

$$G_{\text{RF}} = \left(\left(1 - \frac{40}{s+40} \right) + \frac{40}{s+40} \left(\frac{1}{10} \right) \right) (1-K_{\text{RF}}) + K_{\text{RF}} \quad (24)$$

which is shown in Fig. 12. Substituting α and β back into the Eq. 24, the equation for the “road feel” filter is,

$$G_{RF} = \left(\left(1 - \frac{\alpha}{s + \alpha} \right) + \frac{\alpha}{s + \alpha} \left(\frac{1}{\alpha/\beta} \right) \right) (1 - K_{RF}) + K_{RF}. \quad (25)$$

5

Gain plots of the controller with and without the “road feel” filter G_{RF} are shown in Figs. 13a and 13b. The torque filter has $\alpha=40$ and $\beta=10$, the blending frequency is 37rad/sec, and $K_{max}=1.11$. Five gain traces are shown for K_a increasing linearly from zero to $K_{max}/10$. Fig. 13a shows the blending filter G_{Blend} /torque filter G_f topology and the Fig. 13b shows the effect of adding the road feel filter G_{RF} . It can be seen that the gain of the plot of Fig. 13b plot is significantly lower than the gain of the plot in Fig. 13a at frequencies below 10Hz. As a result, lowering the controller gain improves the disturbance rejection which is transmitted through the steering wheel and felt by the driver.

10

15

At high vehicle speeds, increasing the low frequency pole of the torque filter G_f also improves the disturbance rejection transfer function by minimizing the gain of the implicit lag/lead filter. However, the lag/lead is not eliminated, only minimized, and the tuning dynamic range may be compromised if the pole is placed at too high a frequency.

20

Fig. 14a and 14b show the disturbance gain and phase of the rejection transfer function for the standard blending filter (with the same parameters shown in Fig. 13a and 13b) and the road feel filter G_{RF} . The gain with the road feel filter G_{RF} is about 5db higher than the nominal gain and is improved in the range between 0.5 and 7Hz.

25

Fig. 15a shows the low and high speed assist curves, Fig. 15b shows the low and high frequency assist curves, and Fig. 15c shows the normalized input torque. The input torque starts at zero, steps to 1, steps back to zero, etc. When the input torque is zero, the motor command should also be zero to reduce hesitation and improve flick response.

Fig. 16a and 16b show time domain outputs of the nominal filter (i.e., without the road feel filter G_{RF}) and the nominal+road feel filter G_{RF} , respectively, for an input of 1Nm at a park condition (i.e., vehicle speed 0kph). Fig. 16c and Fig. 16d show time domain outputs of the nominal filter and the nominal+road feel filter G_{RF} for an input of 2Nm at a park condition (i.e., vehicle speed 0kph). Fig. 16a and 16c illustrate the input torque and assist torque. Fig. 16b and 16d illustrate the motor command for the nominal system and for the nominal+road feel filter G_{RF} . For torque below 2Nm, the assist is still within the deadband so no dc assist is required. However, the nominal system has the implicit lag/lead at $(s+40)/(s+4)$ so there is a transient in the motor command that winds up and must decay. The road feel filter G_{RF} cancels out the lag/lead and has no windup. This filter responds to the transients, but does not wind up.

Figure 17a-d shows similar plots to those of Figs. 16a-d except the inputs of 4Nm and 6Nm are used. At 4Nm, the assist torque is outside the deadband. So long as the assist is above 0.5Nm, the solutions with and without the road feel filter G_{RF} are the same. However, when the assist goes to zero, the motor command follows the assist because the road feel filter G_{RF} cancels the effect of the low frequency pole.

Figs. 18a-d and Figs. 19a-d show motor command responses for the same inputs but at 100kph. The results for torques within the deadband are similar to the Park case. However, for the 6Nm input torque case, the road feel filter G_{RF} does not keep the motor command wound up when the input torque goes away. This improves both flick response and the hesitation. The root cause of the wind-up issue is addressed with the Road Feel filter. The low frequency pole is eliminated via pole-zero cancellation when the assist is zero.

Figs. 20a and 20b shows the disturbance rejection plots for the hand wheel free case at zero gain. The gain of the system with the Road Feel filter is slightly above the open loop system below 1Hz and is substantially above the nominal filter.

From the above description of preferred embodiments of the invention, those skilled in the art will perceive improvements, changes and modifications. Such

improvements, changes and modifications within the skill of the art are intended to be covered by the appended claims.

5

TABLE OF REFERENCE NUMBERS

	10	power assist steering system
	12	steering wheel
10	14	pinion gear
	16	input shaft
	18	output shaft
	20	torsion bar
	22	rack or linear steering member
15	24	steerable wheel
	26	steerable wheel
	28	electric assist motor
	30	rotor position sensor
	40	position sensor
20	44	torque sensor
	50	torque signal processing circuit
	53	switch
	54	assist curve circuit
	55	switch
25	56	vehicle speed sensor
	60	low speed assist curve
	66	high speed assist curve
	68	blending filter determination circuit
	70	low pass filter

- 71 high pass filter
- 72 high frequency assist gain circuit
- 74 circuit
- 79 summing circuit
- 5 80 adaptive torque filter
- 81 road feel filter G_{FR}
- 83 circuit
- 90 motor controller
- 94 inputs
- 10 96 drive control circuit
- 100 plurality of power switches
- 101 transfer function
- 102 motor command input signal τ_m
- 103 transfer function
- 15 104 sensed torque output τ_s
- 105 disturbance rejection transfer function
- 106 disturbance torque τ_d
- 107 gear ratio feedback signal r_m/r_p
- 108 sensitivity transfer function
- 20 110 gearing ratio
- 116 summing circuit

What is claimed is:

1. An apparatus for controlling a steering assist system, said steering assist system providing assist in response to a steering control signal, said steering assist
5 system including a controller having gain, said apparatus comprising:

torque sensing means operatively connected to a vehicle hand wheel for providing a torque signal indicative of an applied steering torque;

blending filter means connected to said torque sensing means for providing a blended filter torque signal having a first functional characteristic at a torque
10 frequency less than a blending frequency and a second functional characteristic at torque frequencies greater than said blending frequency;

an adaptive filter means that filters said blended filter torque signal for providing an adaptive filter torque signal for maintaining stability at substantially all vehicle speeds;

15 a road feel filter means connected to said adaptive filter means for providing a modified adaptive filter torque signal for removing a lag-lead induced by an interaction of said adaptive filter means and said blending filter means at substantially zero gain;

steering assist means for providing steering assist in response to a control
20 signal; and

control means operatively connected to said road feel filter means for providing said control signal to said steering assist means in response to said modified adaptive filter torque signal, said road feel filter means filtering said lag-lead from said adaptive filter torque signal for allowing road feel to be transmitted through said hand wheel at
25 said substantially zero gain.

2. The apparatus of claim 1 wherein said road feel filter means is inhibited from acting on said adaptive filter torque signal from said interaction of said blended filter means and said adaptive filter means at a substantially high gain.

3. The apparatus of claim 1 wherein said road feel filter means is inhibited from acting on said adaptive filter torque signal from said interaction of said blended filter means and said adaptive filter means at a substantially minimal gain.

5

4. The apparatus of claim 1 wherein a low frequency pole of said adaptive filter means is eliminated by said road feel filter means at said substantially zero gain.

5. An apparatus for controlling a steering assist system, said steering assist
10 system providing assist in response to a steering control signal, said apparatus comprising:

a torque sensing system operatively connected to a vehicle hand wheel for providing a torque signal indicative of an applied steering torque;

a blending filter connected to said torque sensing system for providing a
15 blended filter torque signal;

an adaptive torque filter for filtering said blended filter torque signal for providing an adaptive filter torque signal for maintaining stability at substantially all vehicle speeds;

a road feel filter connected to said adaptive torque filter for providing a
20 modified adaptive filter torque signal for removing a lag-lead induced by an interaction of said adaptive torque filter and said blending filter at substantially zero gain;

steering assist device for providing steering assist in response to a control signal; and

25 a controller having gain and operatively connected to said road feel filter for providing said control signal to said steering assist device in response to said modified adaptive filter torque signal, said road feel filter filtering said lag-lead from said adaptive filter torque signal for allowing road feel to be transmitted through said hand wheel at said substantially zero gain.

6. The apparatus of claim 5 wherein said road feel filter is inhibited from acting on said adaptive filter torque signal from said interaction of said blended filter and said adaptive filter at a substantially high gain.

5

7. The apparatus of claim 5 wherein said road feel filter is inhibited from acting on said adaptive filter torque signal from said interaction of said blended filter and said adaptive filter at a substantially minimal gain.

10

8. The apparatus of claim 5 wherein a low frequency pole of said adaptive filter is eliminated by said road feel filter at said substantially zero gain.

15

9. The apparatus of claim 5 further comprising a drive control circuit, a set of power switches, and a rotor position sensor connected to said controller for controlling electrical energy to said steering assist device.

10. A method for controlling a steering assist system that provides steering assist in response to a steering control signal, said steering assist system including a controller having gain, said method comprising the steps of:

20

measuring an applied steering torque and providing a torque signal indicative of said measured applied steering torque;

applying a blended filter to said torque signal for producing a blended torque signal;

25

applying an adaptive filter to said blended filter torque signal for producing an adaptive filter torque signal;

applying a road feel filtering to said adaptive filter torque signal for removing lag-lead from said adaptive filtered torque signal for producing said steering control signal; and

providing steering assist in response to said steering control signal.

11. The method of claim 10 wherein said step of applying said road feel filtering filters said lag-lead from said adaptive filter torque signal for allowing road feel to be transmitted through said hand wheel at said substantially zero gain.

5

12. The method of claim 10 wherein said step of applying said road feel filtering eliminates a low frequency pole of said adaptive filter means at said substantially zero gain.

10

13. The method of claim 10 wherein said step of applying said road feel filtering is inhibited from acting on said adaptive filter torque signal at a substantially minimal gain.

15

14. The method of claim 13 wherein said step of applying said road feel filtering allows said lag-lead control strategy to pass through said road feel filtering.

20

15. The method of claim 10 wherein said step of applying said road feel filtering is inhibited from acting on said adaptive filter torque signal at a substantially high gain.

16. The method of claim 15 wherein said step of applying said road feel filtering allows said lead lag control strategy to pass through said road feel filtering.

25

17. The method of claim 10 wherein said step of applying said blended filtering torque provides a blended filter torque signal having a first functional characteristic at a torque frequency less than a blending frequency and a second functional characteristic at torque frequencies greater than said blending frequency.

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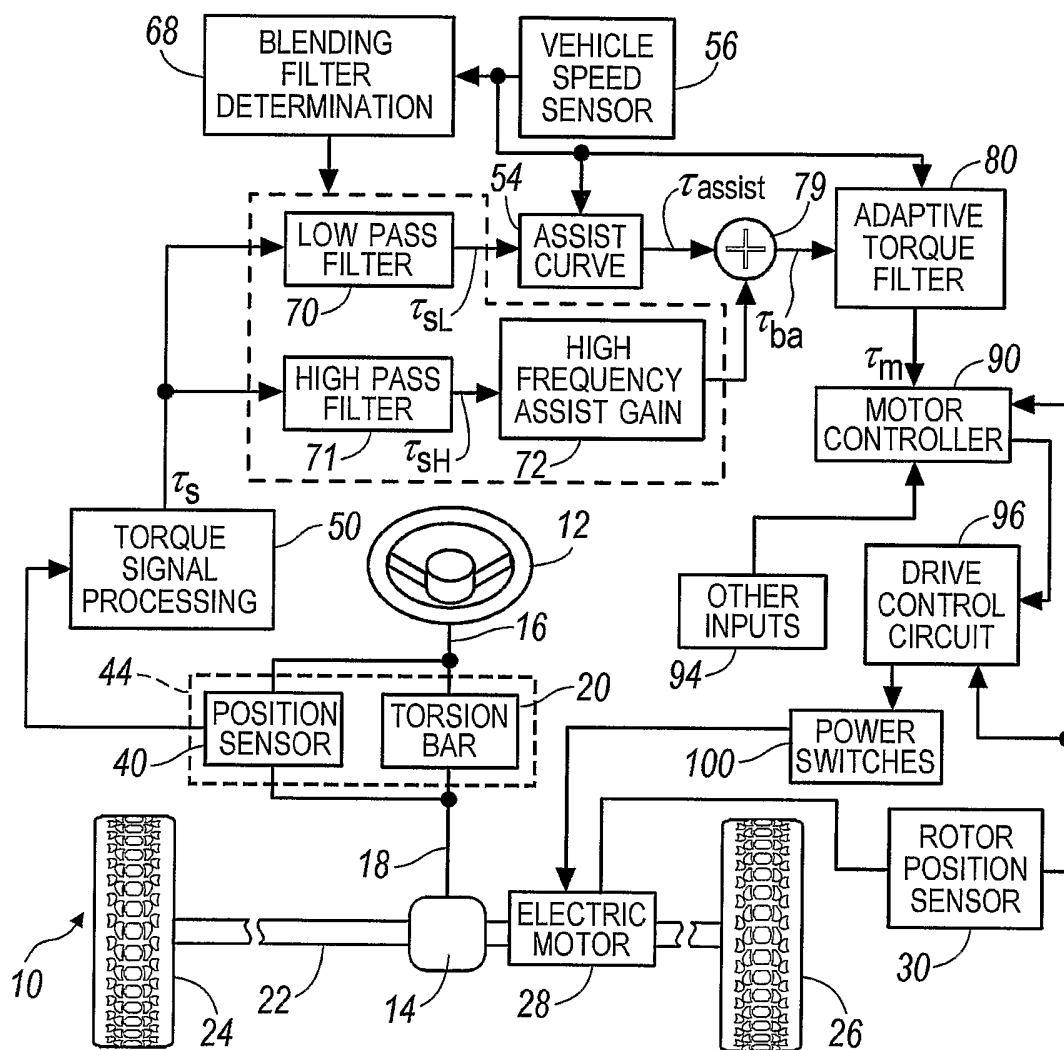


FIG. 1

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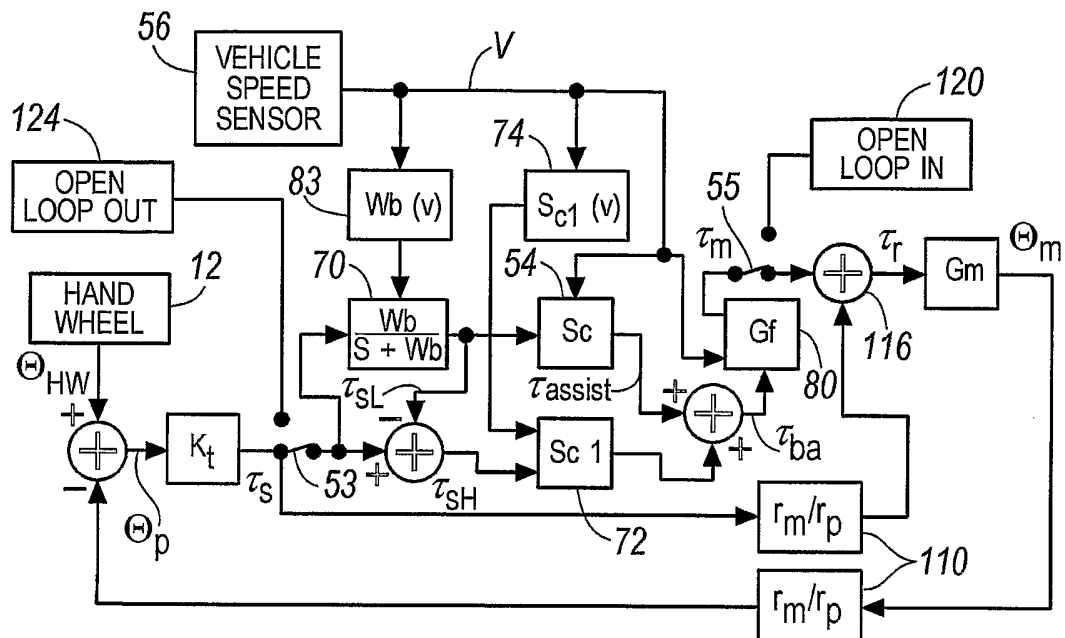


FIG. 2

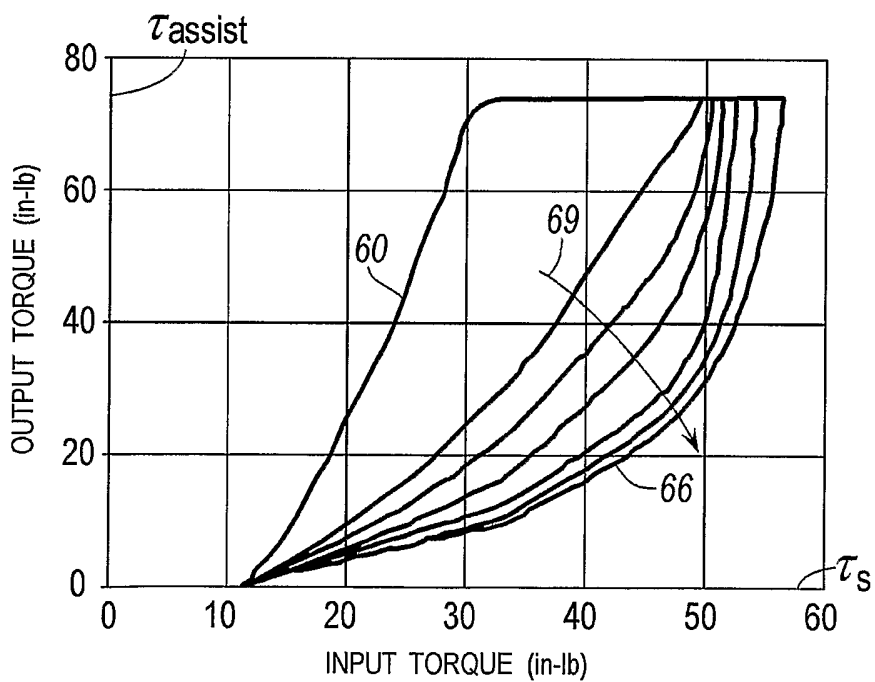


FIG. 3

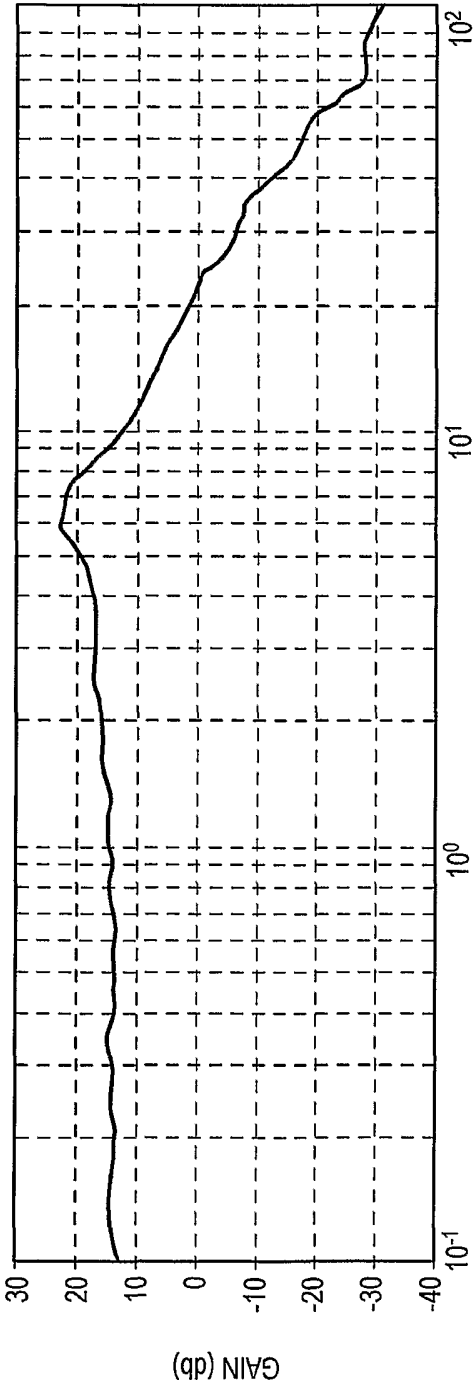


FIG. 4A

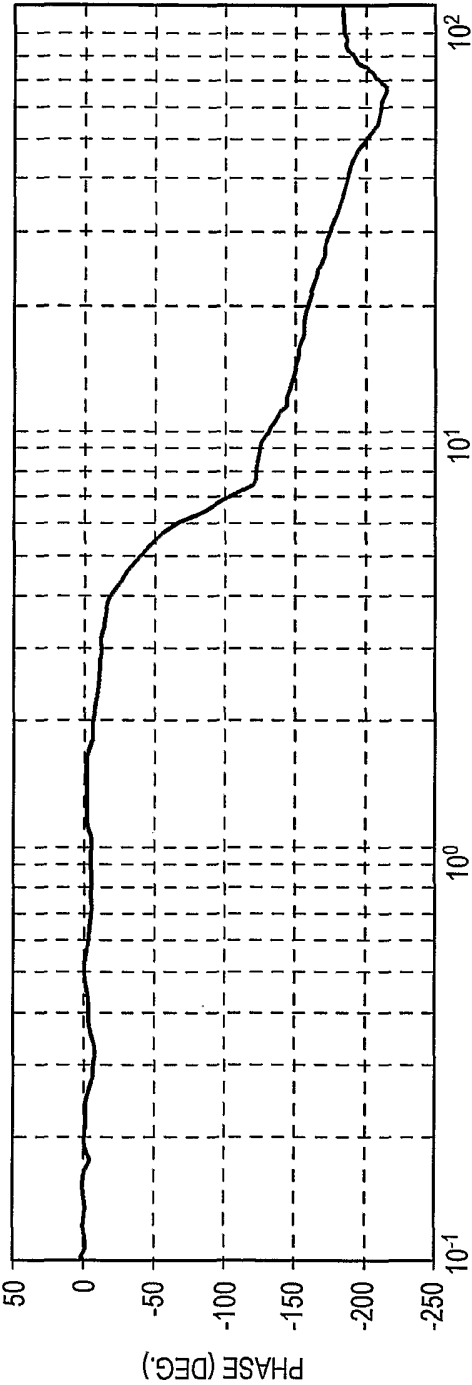
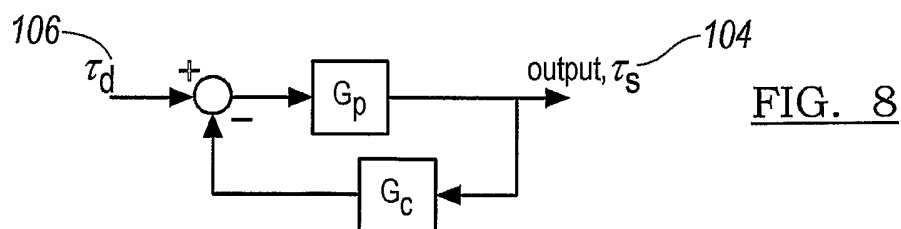
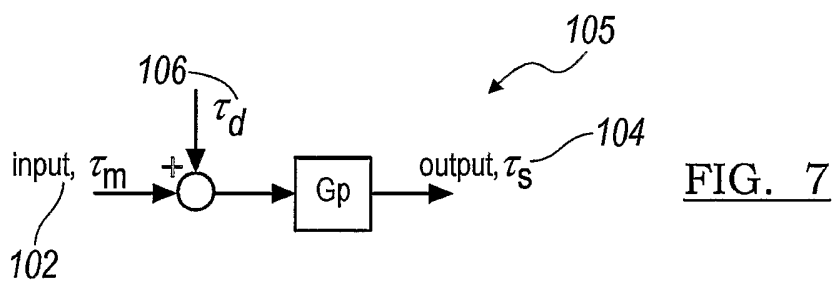
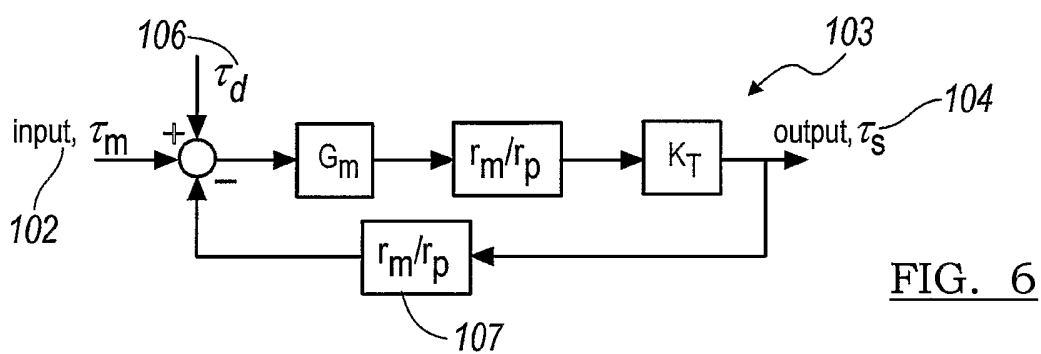
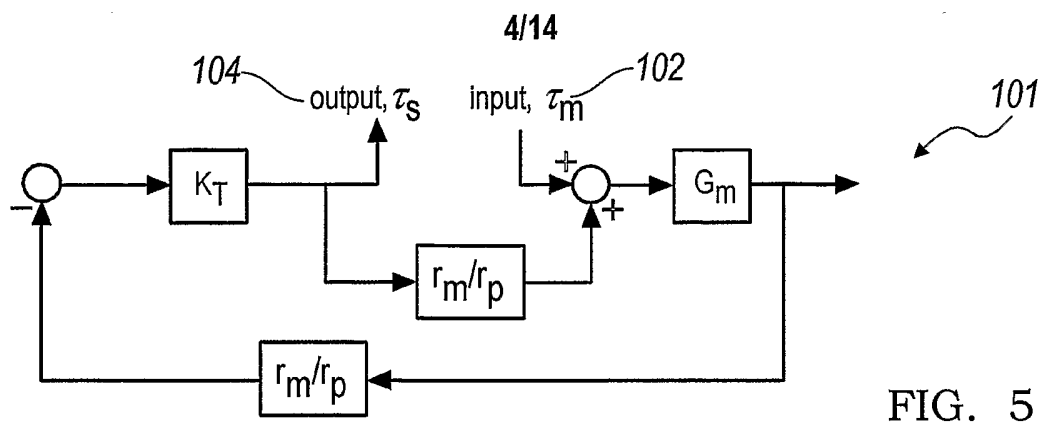


FIG. 4B



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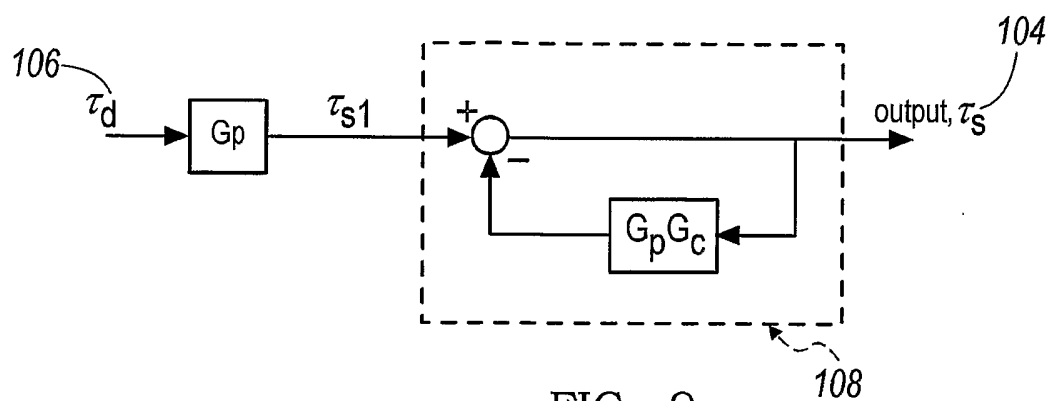


FIG. 9

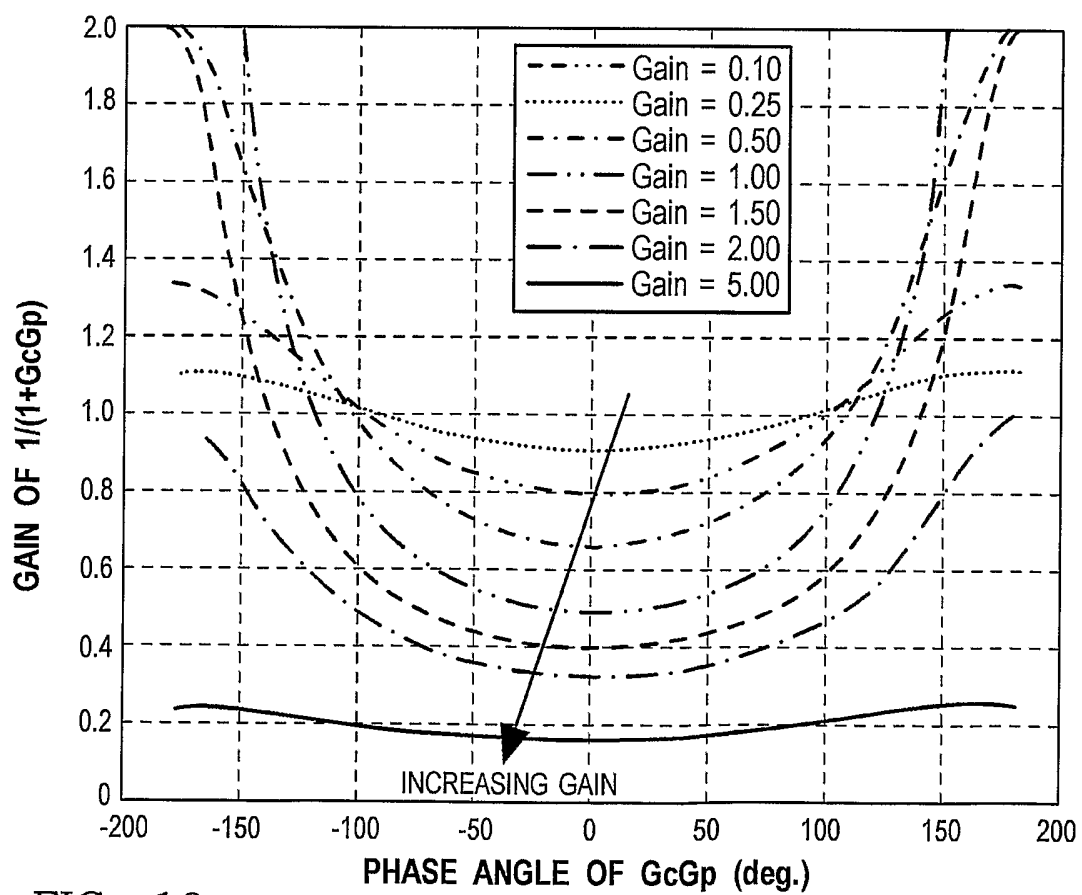
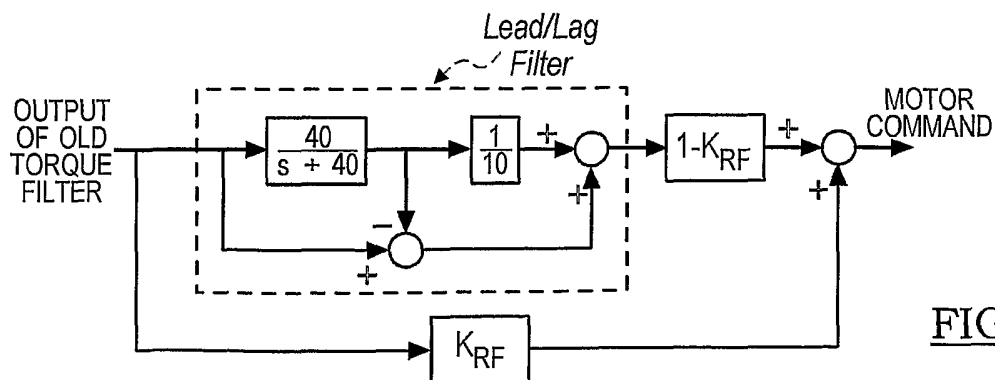
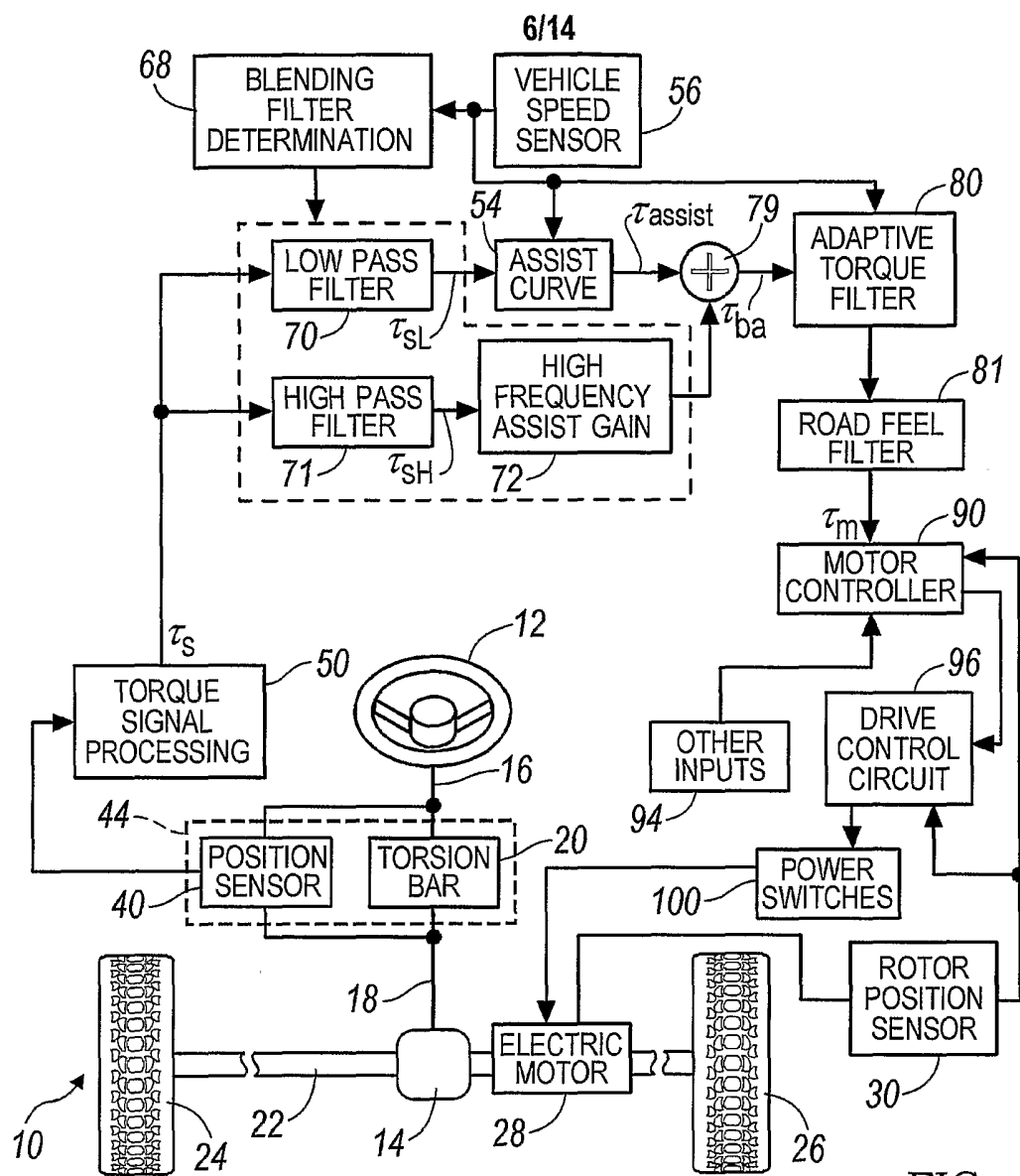
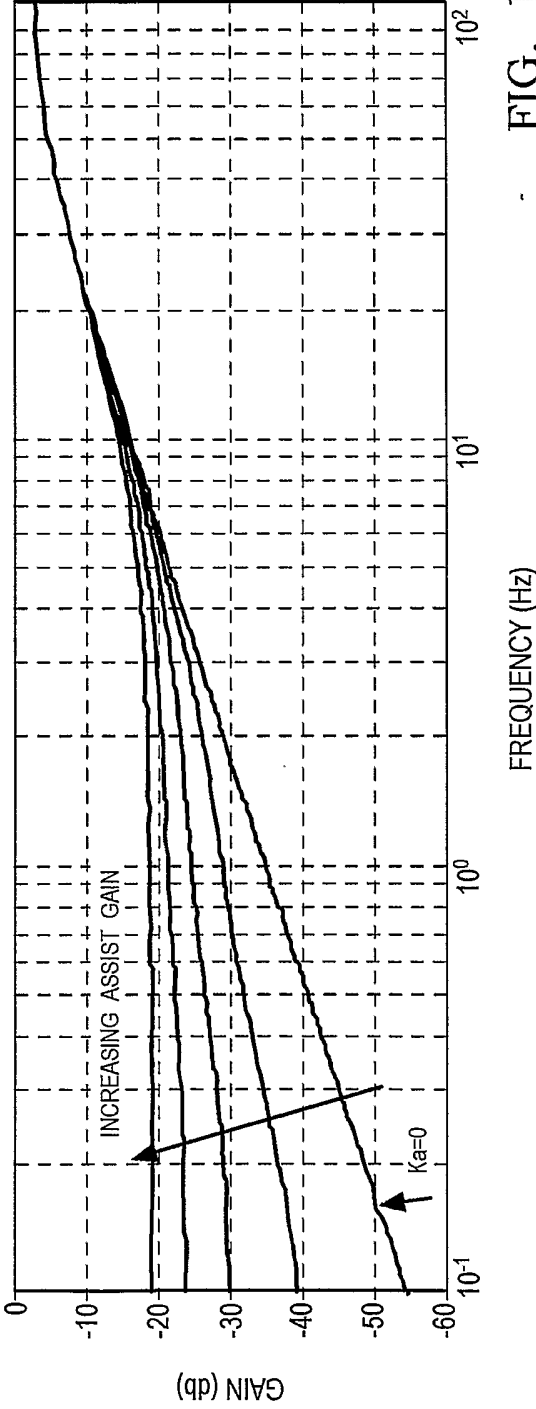
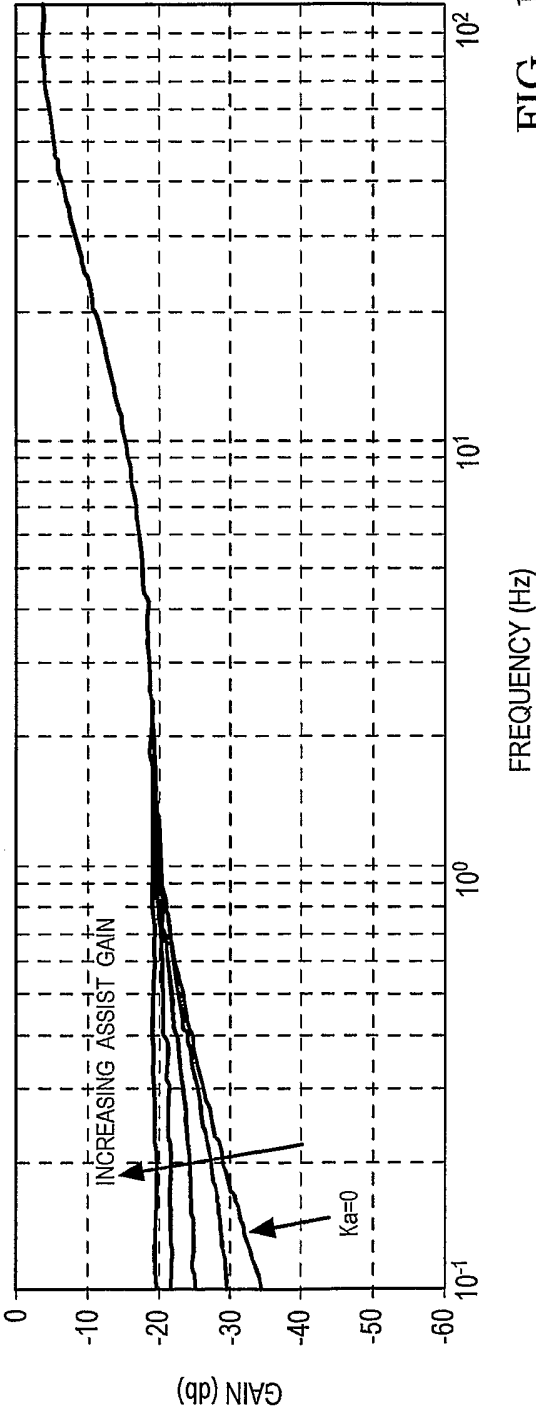


FIG. 10





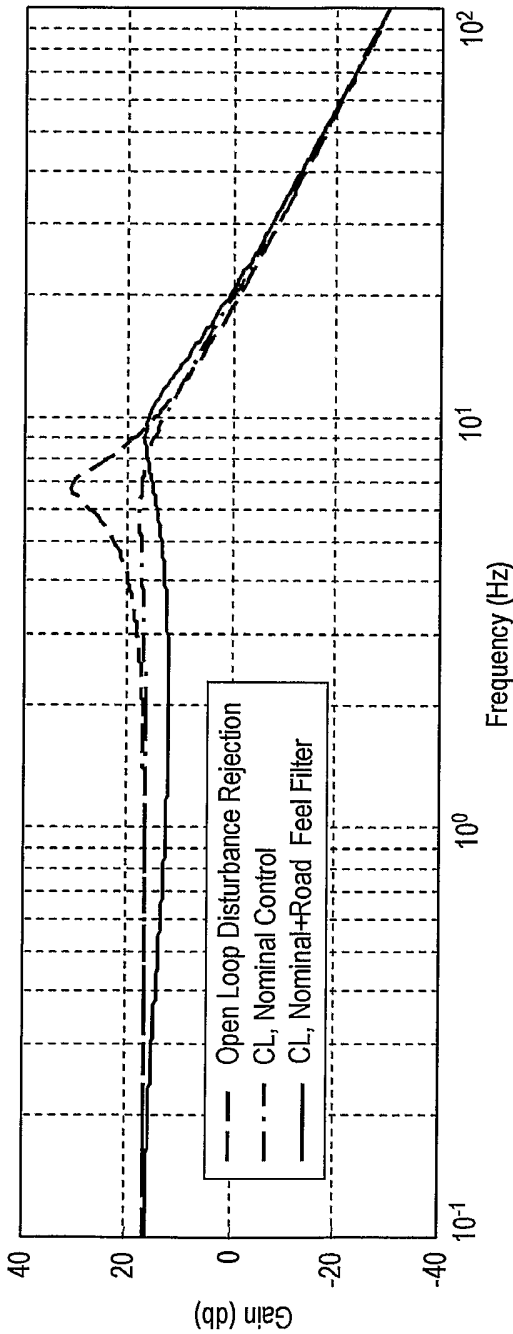


FIG. 14A

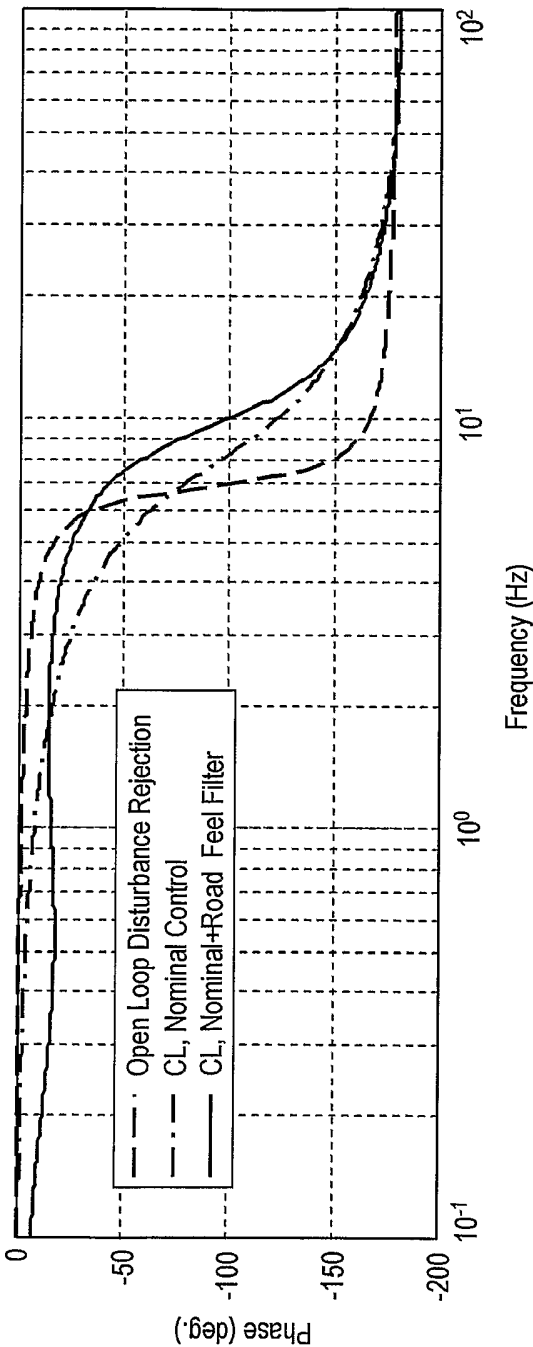
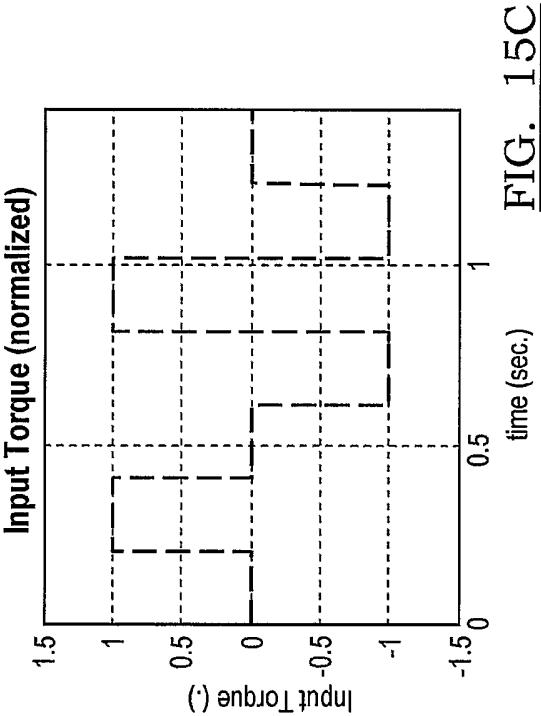
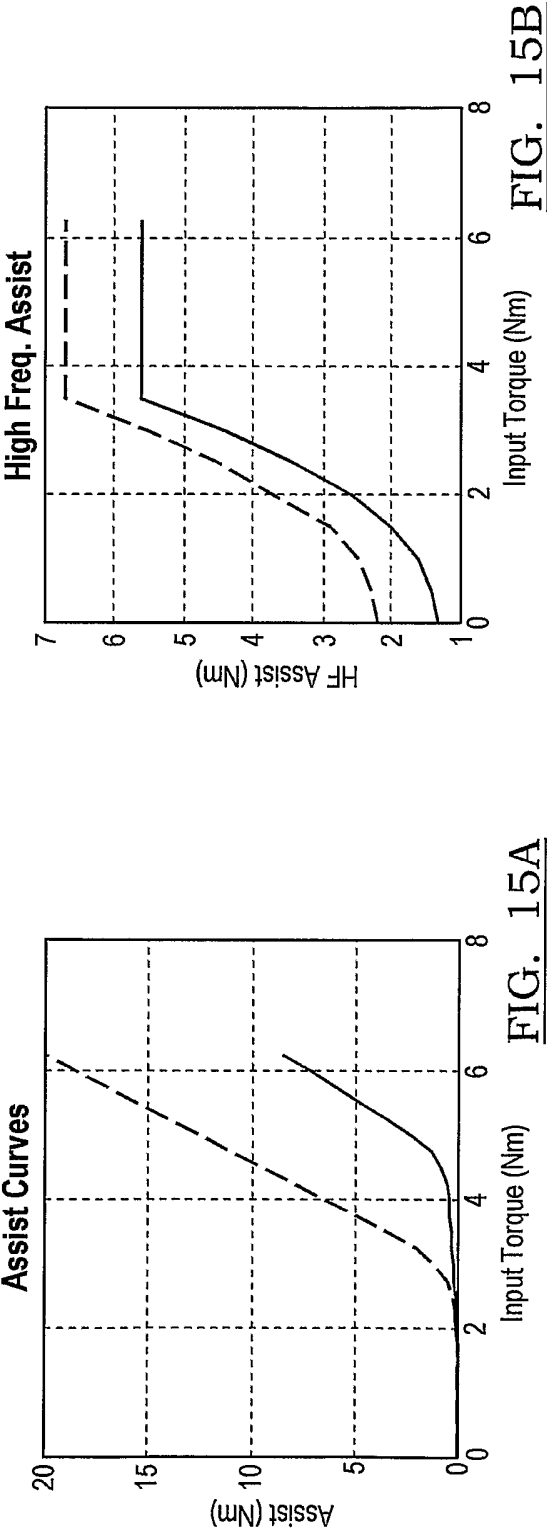
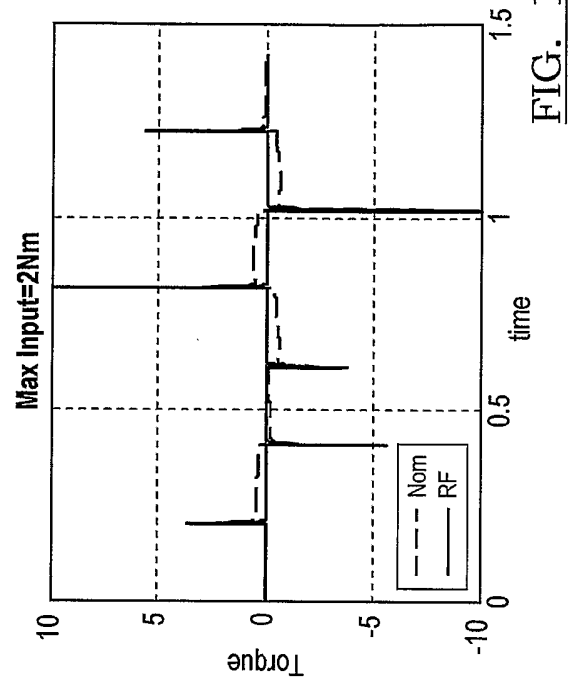
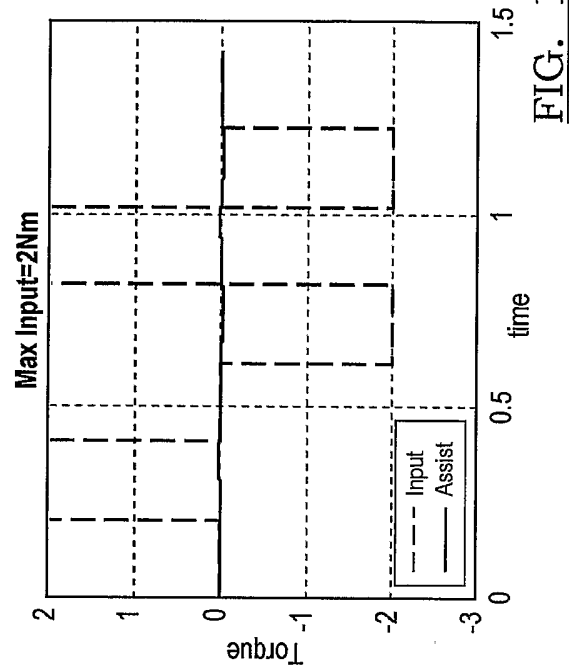
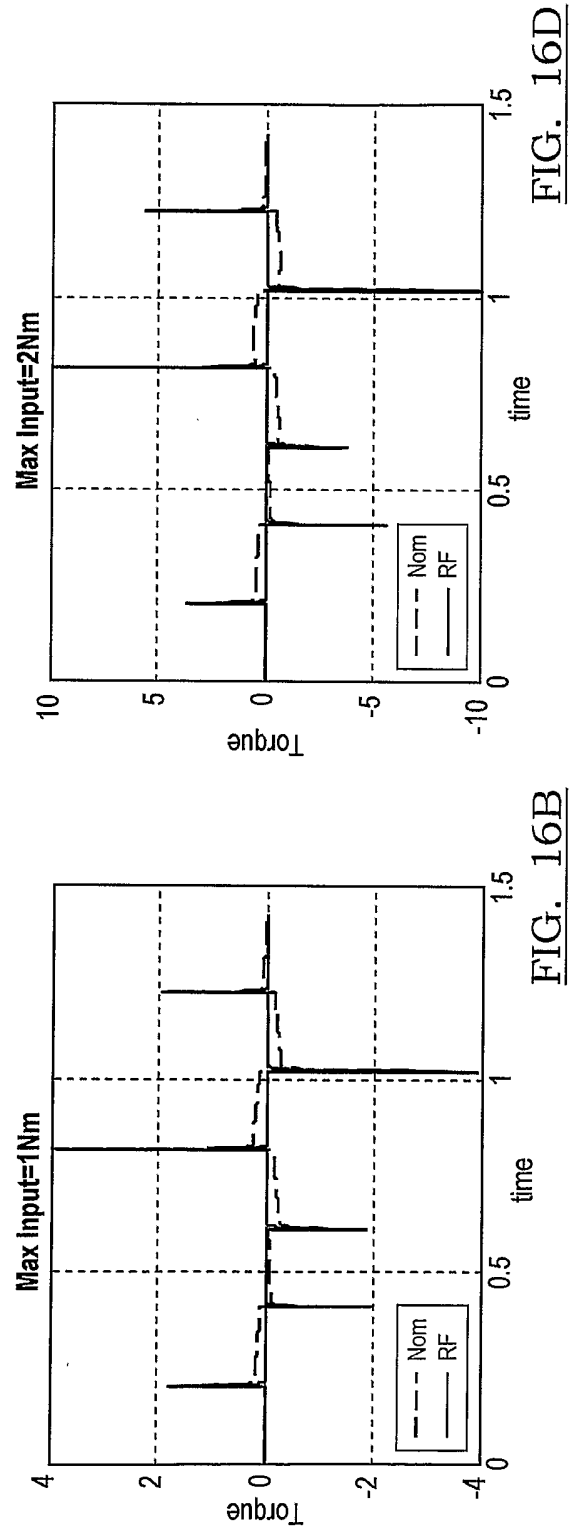
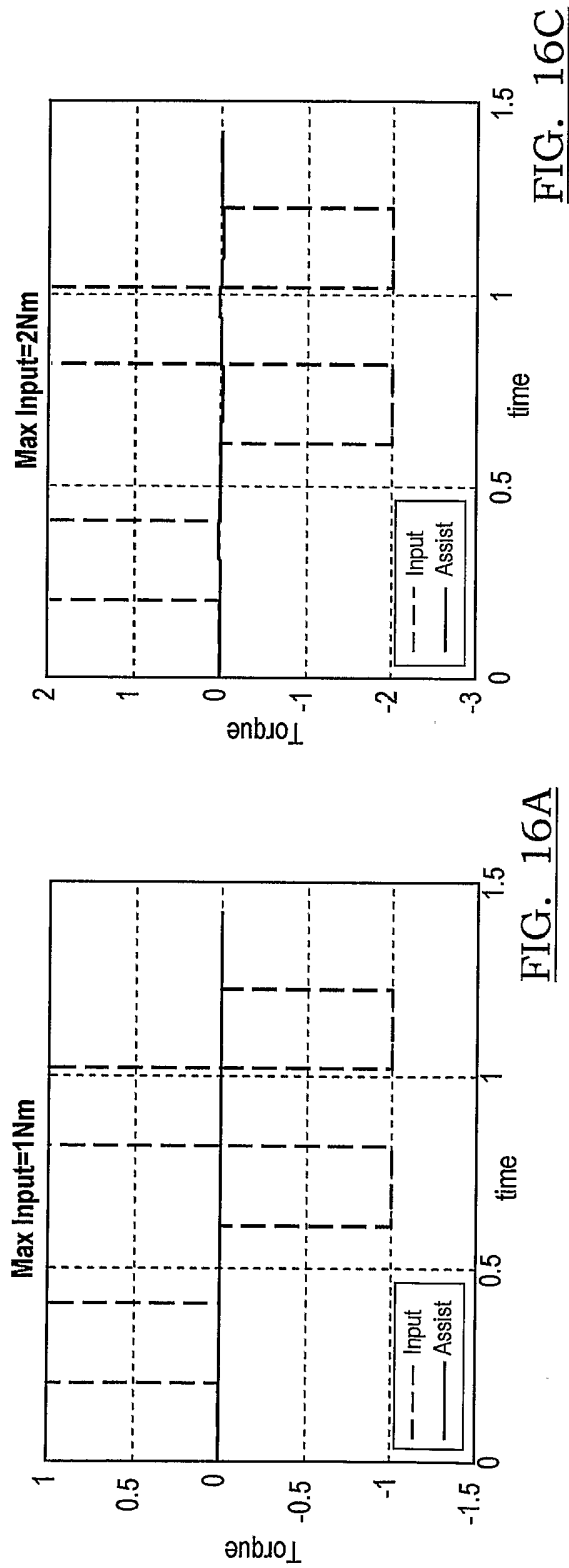
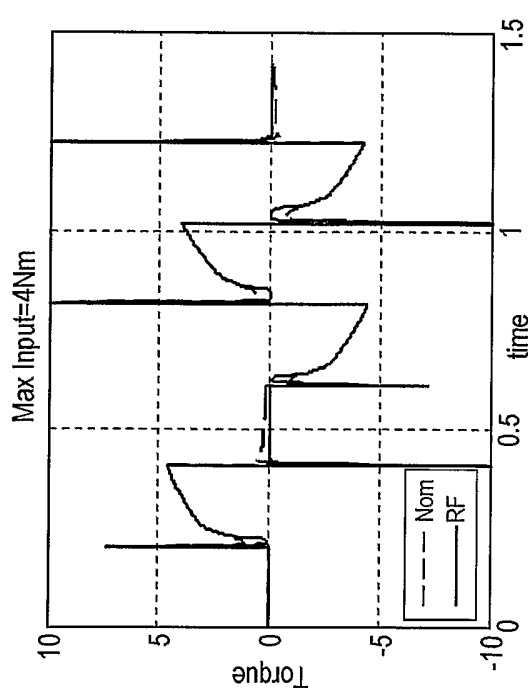
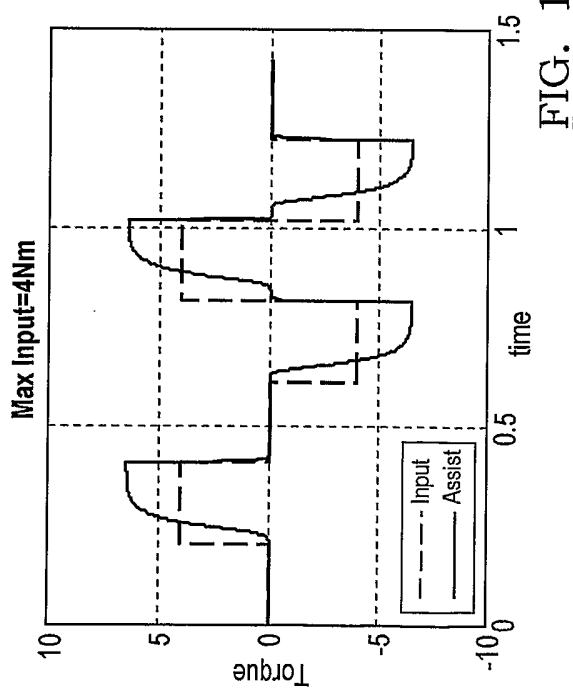
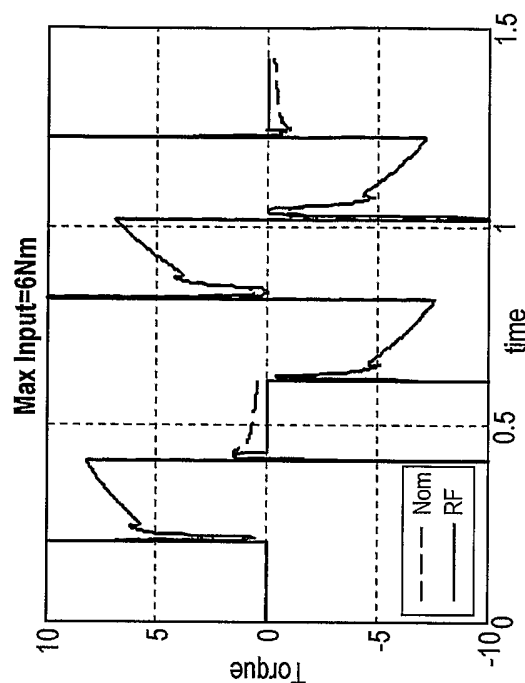
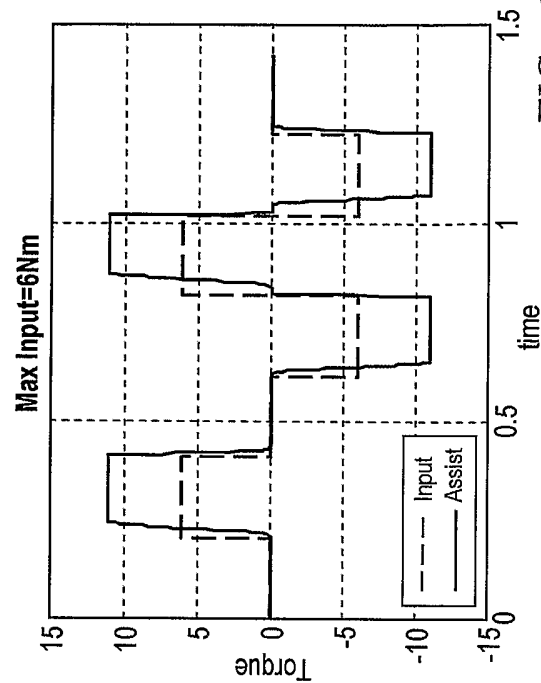


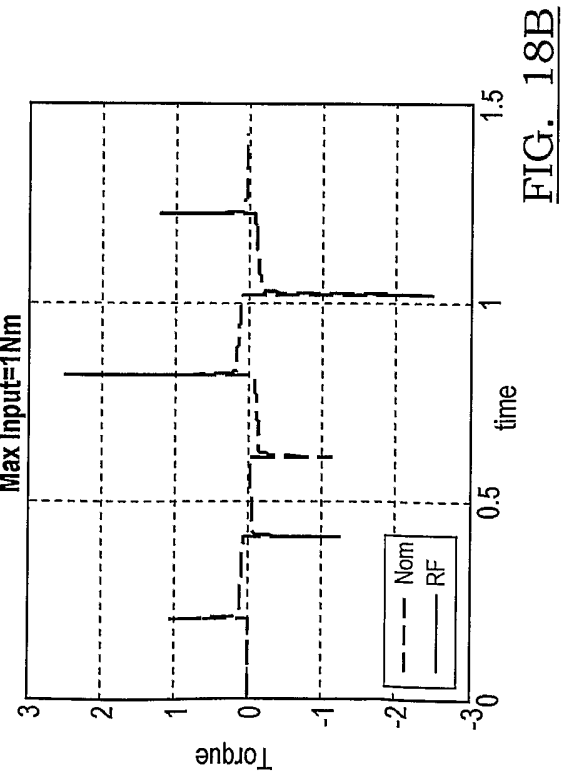
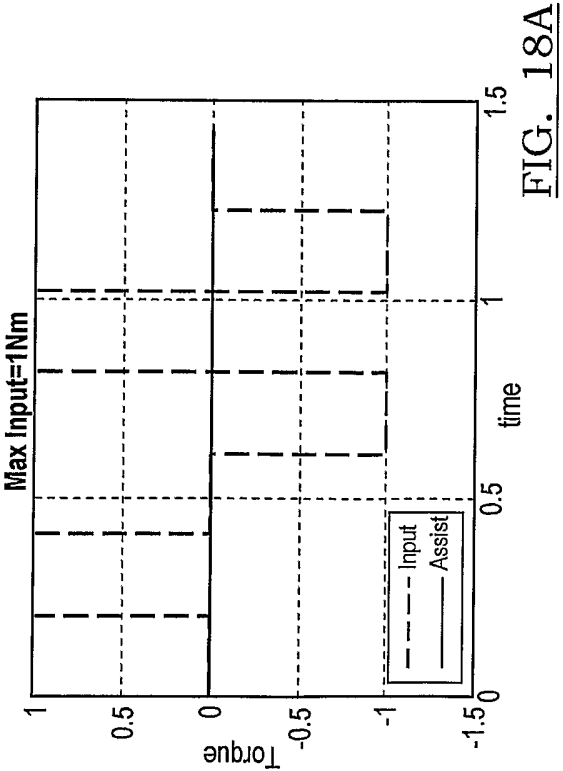
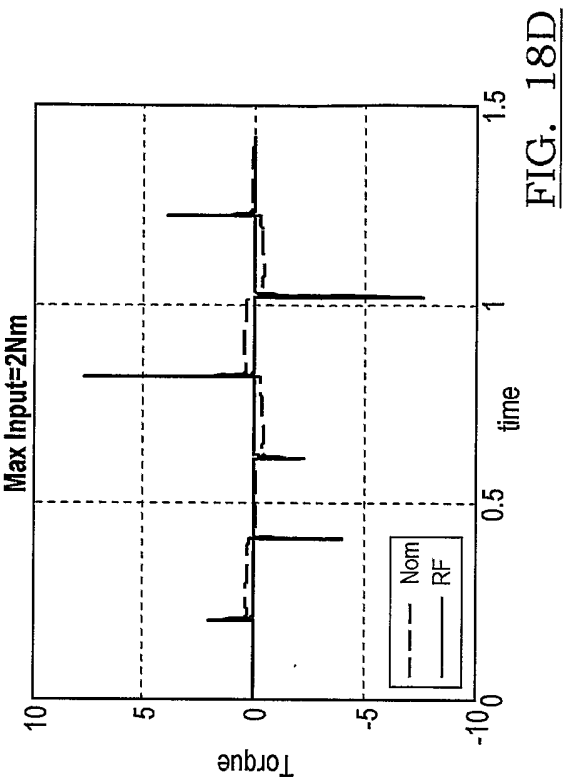
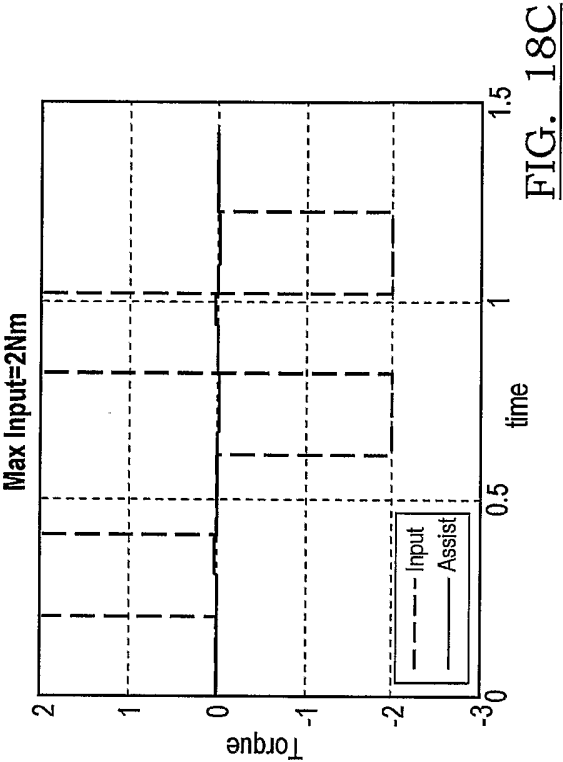
FIG. 14B

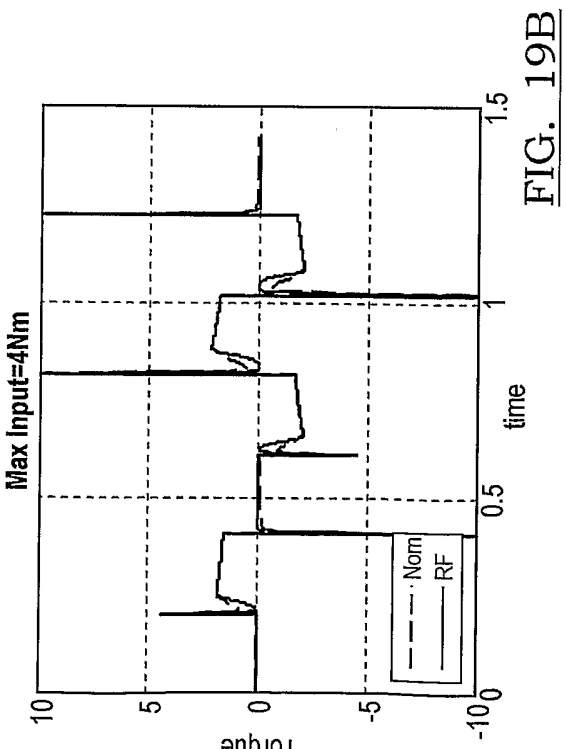
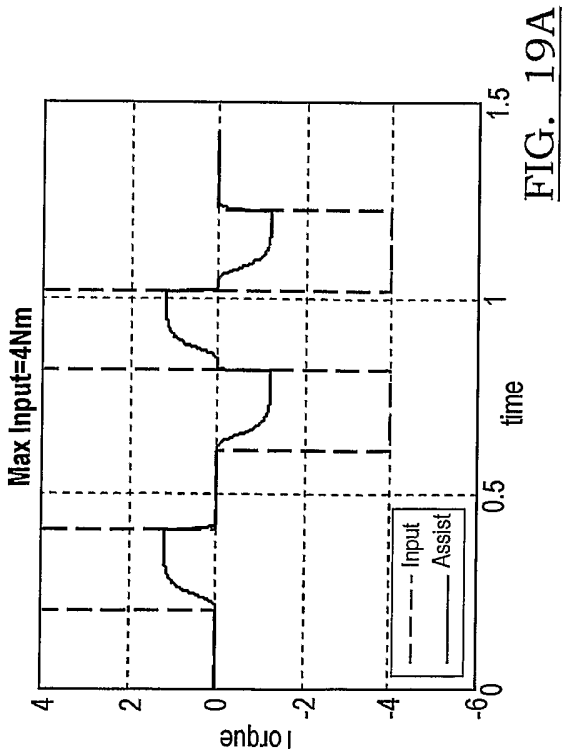
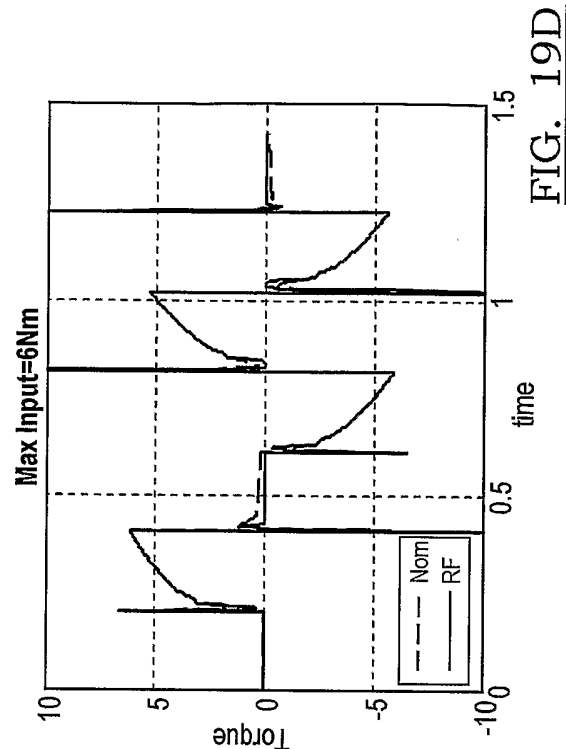
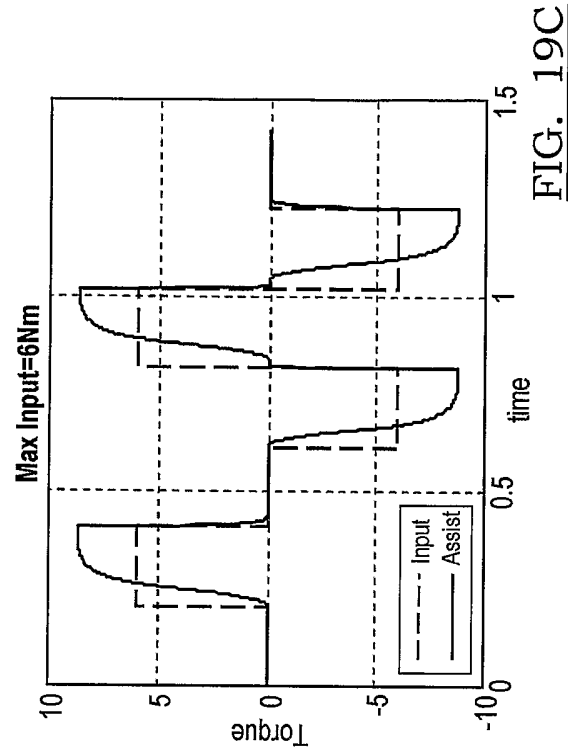






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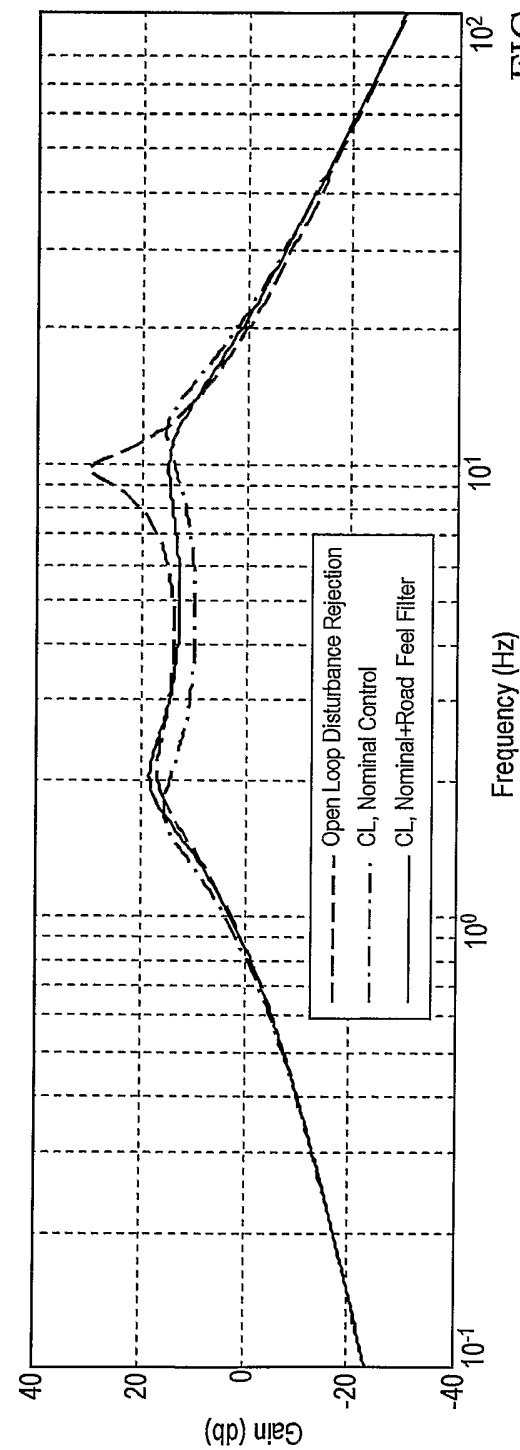


FIG. 20A

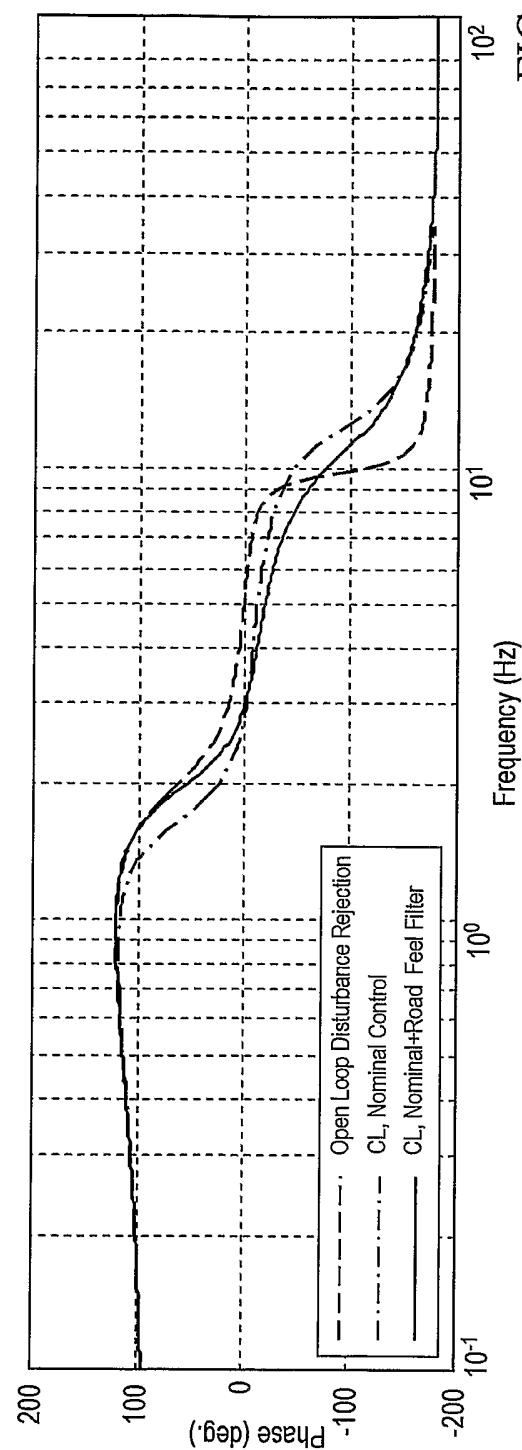


FIG. 20B

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2006/009313

A. CLASSIFICATION OF SUBJECT MATTER
 INV. B62D6/00 B62D5/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
 B62D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 504 403 A (MCLAUGHLIN ET AL) 2 April 1996 (1996-04-02) cited in the application the whole document	1,5,10
A	US 5 257 828 A (MILLER ET AL) 2 November 1993 (1993-11-02) cited in the application the whole document	1,5,10
A	EP 0 683 086 A (TRW INC) 22 November 1995 (1995-11-22) the whole document	1,5,10
A	US 2003/055546 A1 (DEMERLY JON D ET AL) 20 March 2003 (2003-03-20) the whole document	1,5,10
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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search

6 July 2006

Date of mailing of the international search report

17/07/2006

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Van der Veen, F

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2006/009313

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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International application No

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