INTERNATIONAL JOURNAL OF MATHEMATICAL SCIENCES, TECHNOLOGY AND HUMANITIES
www.internationalejournals.com

ISSN: 2249–5460
AVAILABLE ONLINE AT WWW.INTERNATIONALEJOURNALS.COM
INTERNATIONAL EJOURNALS
International Journal of Mathematical Sciences, Technology and Humanities 109 (2014) 1164–1176

A Study on Active Electromagnetic Suspension System

Velivela Lakshmikanth Chowdary[#] and Katuru Venkata Naga Dinesh Kumar[$]
[#] Student, Department of Mechanical, Sarojini Institute of technology, A.P.INDIA.
[*] Assoc. Professor, Department of ECM, KL University, A.P., INDIA.
[#] Student, Department of Mechanical, Sarojini Institute of technology, A.P.INDIA.
jaswanthbhargav@gmail.com ,drsyedumar@kluniversity.in.

Abstract— This paper introduces a service robot which performs the repetitive task of welcoming people graciously both by a sweet recorded message and hand gesture representing "Namastae" – an Indian tradional method wishing of people. Most commonly we observe people dressed in the getups of Mickey mouse, Donald duck, Teddy bear etc., near schools, colleges, offices, in parties and marriages etc. Here the people wear only dress and performs the task of wishing unknown people mechanically which is really a mind-numbing task. In this paper we designed a service robot that acts as a host in receiving people and performs the same task for hours without getting weary. This is a low cost flexible robot which can be designed and constructed without difficulty.

Keywords—Ping sensor, Arduino, servos, relays

I. INTRODUCTION

A robot is a mechanical or virtual agent, usually an electro-mechanical machine that is guided by a computer program or electronic circuitry. Robots have replaced humans in the assistance of performing those repetitive and dangerous tasks which humans prefer not to do, or are unable to do due to size limitations, or even those such as in outer space or at the bottom of the sea where humans could not survive the extreme environments. Modern robots are classified into different categories such as mobile robots, commercial or industrial robots, cobots or service robots based on their performance features[1]. In this project we built a service robot which perform the repetitive task of welcoming people both by recorded voice message and by hand movement representing "Namastae" in its vicinity. Usually when we invite people to home, office, marriage functions or parties etc., we need to assign a person to receive them and greet at the entrance. If this greeting is to a limited amount of people then the task appears simpler. But if it is to greet hundreds or thousands of people, then the task appears complex and boring because the person has to wait for hours and repeat the same process of wishing with affection and enthusiasm carrying a broad smile. Hence we tried to simplify the complexity by developing a robot which could stand at the entrance and wish each and every person within its vicinity. The idea of a robot greeting them in an Indian traditional style, along with a hand gesture "NAMASKAR" appeals to people. The style can be changed by making minimum changes in the program based upon the country. It does not get tired or bored and hence can perform its duty for longer hours. Children attending the function also will be more eager and excited at such reception. We present our exploration of the emotional impact that abstract mechanical or robot motion has on human-robot interaction (HRI). We argue for the importance of designing for the fundamental characteristics of physical robot motion .We discuss our design approach and motion planning as a process of detailing a task into discrete motions. We detail our results and explain how different styles of robot motion were mapped to emotional responses in human observers. We believe that our findings can inform and provide important insight into the purposeful use of motion as a design tool in social human-robot interaction.

BLOCK DIAGRAM OF ROBOT:

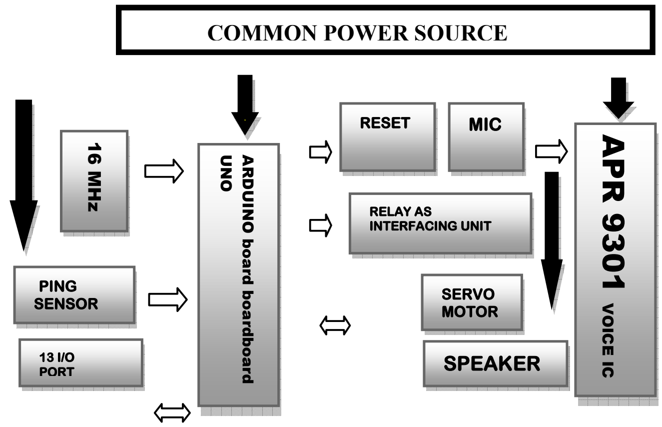

FIG 1: Block diagram of Namaskar Robot with voice

Figure1 represents the block diagram of the Namaskar robot with voice. Different components, modules and development boards are placed in the block diagram. The description of each block is as follows:

Power Source:

A common power supply provides to all the required modules. The modules require an operating voltage of 5-volts and current in milliamps. Hence a IC7805 positive series voltage regulator is used to provide stabilized voltage. The output from the regulator is driven to different blocks.

Sensor:

The ping sensor is an ultrasonic sensor which uses SONAR to determine the distance of an object in its vicinity. This sensor is used as eyes to the robot to detect an obstacle. The Ultrasonic ranging module used here is HC - SR04 because it provides range accuracy and is available at low cost. It provides 2cm-400cm non-contact measurement function with a ranging accuracy up to a distance of 3mm. The modules includes ultrasonic transmitters, receiver and control circuit.

Voice Playback IC:

Audio playback product line is ideally suited to any electronic appliance that requires the audio playback of pre-recorded data including, kiosk, toys, signage, and security applications.

Relay:

A relay is an electrically operated switch. Current flowing through the coil of the relay creates a magnetic field which attracts a lever and changes the switch contacts.

Microphone:

A Microphone is af *transducer* - a device which converts energy from one form to another. Microphones convert acoustical energy (sound waves) into electrical energy (the audio signal).

Microcontroller:
A microcontroller is a single integrated chip that contains the processor, non-volatile memory for the program, volatile memory for input and output clock and an I/O control unit. It is also called a "computer on a chip,". Microcontrollers are used in automatically controlled products and devices, such as automobile engine control systems, implantable medical devices, remote controls, office machines, appliances, power tools, toys and other embedded systems
.

II. MICROCONTROLLER BASED ON ARDUINO

Arduino: Arduino is a tool for making computers that can sense and control more of the physical world than Desktop computer. It is an open-source physical computing platform based on a simple Microcontroller board. Arduino can be used to develop interactive objects, taking inputs from a variety of switches or sensors, and controlling a variety of lights, motors, and other physical outputs.

There are many other microcontrollers and microcontroller platforms available for physical computing. Parallax Basic Stamp, Net media's ,MIT's Handy board, and many others offer similar functionality. All of these tools take the messy details of microcontroller programming and wrap it up in an easy-to-use package whereas Arduino simplifies the process of working with microcontrollers and is more advantageous to interested amateurs over other systems:

- **Inexpensive** –

  Arduino boards are relatively inexpensive compared to other microcontroller platforms.

- **Open source and extensible software** –

  The Arduino software is published as open source tools. The language can be expanded through C++ libraries, and people wanting to understand the technical details can make the leap from Arduino to the AVR C programming language on which it's based.

The ideal automotive suspension would, independently, absorb road shocks rapidly and would return to its normal position slowly while maintaining optimal tire to road contact. However, this is difficult to achieve passively, where a soft spring allows for too much movement and a hard spring causes passenger discomfort due to road irregularities. Passenger comfort (combined with handling and safety) is an ever increasing demand, where everybody expects ever improving comfort and handling from the automotive industry. Albeit that a dearth of publications exists regarding passenger comfort, it was assumed that general comfort is improved when two conditions are minimized:
• Motion sickness, ~1 Hz [6], and
• Head toss, ~2-8 Hz [7].

A. Motion sickness
Motion sickness, especially when reading, is a common by-product of exposure to optical depictions of inertial motion [8]. This phenomenon, called visually induced motion sickness (VIMS), has been reported in a variety of virtual environments, such as fixed-base flight and automobile simulators [9, 10, 11]. Further Gahlinger [12] discussed that motion sickness occurs most commonly with acceleration in a direction perpendicular to the longitudinal axis of the body, which is why head movements away from the direction of motion are so

provocative. He further mentioned that vertical oscillatory motion (appropriately called heave) at a frequency of 0.2 Hz is most likely to cause motion sickness, although that the incidence of motion sickness falls quite rapidly at higher frequencies. This results in the design criteria for active systems that frequencies (lower than 1 Hz) need to be eliminated. This is underlined by surveys documenting that motion sickness occurs in 58 % of the children [6].

B. Head toss

Head toss happens when a car makes a sudden roll motion, e.g. occurring when one tire drives through a deep hole. This is not due to optical depictions but since the receptor mechanisms of the three orthogonally oriented canals in each inner ear are activated by angular acceleration of the head [12]. This especially occurs when a suspension with coupled left and right wheels is used as is the case with passive anti-roll bars. At frequencies below 1-2 Hz the head moved with the body, but in the frequency range of 2-8 Hz the amplitude of head acceleration is augmented indicating that oscillation about a centre of rotation low in the body may induce large angular movements in this frequency range because of the linear component of acceleration delivered at the cervical vertebrae. At higher frequencies, the acceleration at the head was attenuated with an associated increase in phase lag, probably due to the absorption of input acceleration by the upper torso [13]. Hence, the ideal suspension system should minimize the frequency response of the sprung mass displacement to the road disturbances in the band between 0.2 Hz and 10 Hz while maintaining a stiff ride during cornering. However, one of the main problems of an active suspension system is the absence of a fixed reference position and hence, only relative displacements can be measured. Next to that, it is difficult to distinguish the situation of roll during cornering and the condition where the right wheel experiences a different bump then the left wheel. Therefore, different sensor inputs, e.g. position, speed, acceleration, force and roll angle are preferred where, based upon these measurements, the exact state of the vehicle can be estimated in order to control the active suspension system.

Fig. 2. ARC system of BMW using a hydraulic rotary actuator [10].

III. ACTIVE SUSPENSIONS

A. Hydraulic Systems

Due to the high force density, ease of design, maturity of technology, and commercial availability of the various parts, hydraulic systems are commonly used in body control systems. As an example, BMW has recently developed an antiroll control (BMW-ARC) system by placing a hydraulic rotary actuator in the center of the antiroll bar at the rear of the vehicle [10], as shown in Fig. 2. Another example is given by the active body control system of Mercedes [21], which uses high-pressure hydraulics to pre stress the spring, hence generating antiroll forces without coupling the left and right wheels (as in the case of an antiroll bar). All commercial body control systems use hydraulics to provide the active suspension system to improve vehicle roll behavior and ride control, where the main advantages of the hydraulic system are as follows:

1) Very high force density;
2) ease of control;
3) ease of design;
4) Commercial availability of the various parts;
5) Reliability;
6) Commercial maturity.

The main disadvantages of the hydraulic system are as follows:
1) Considered inefficient due to the required continuously pressurized system;
2) Relatively high system time constant (pressure loss and flexible hoses);
3) Environmental pollution due to hose leaks and ruptures, where hydraulic fluids are toxic;
4) Mass and intractable space requirements of the total system, including supply system, even though it mainly contributes to the sprung mass.

Hydraulic systems already proved their potential in commercial systems with regard to active roll control (ARC) since the bandwidth requirement is very small (order of hertz); however, concerning reduction of road vibrations, the performance of the hydraulic system is insufficient.

B. Electromagnetic Systems

An electromagnetic suspension system could counter the disadvantages of a hydraulic system due to the relatively high bandwidth (tens of hertz), and there is no need for continuous power, ease of control, and absence of fluids. Linear motion can be achieved by an electric rotary motor with a ball screw or other transducers to transform rotary motion to linear translation. However, the mechanism required to make this conversion introduces significant complications to the system. These complications include backlash and increased mass of the moving part due to connecting transducers or gears that convert rotary motion to linear motion (enabling active suspension). More important, they also introduce infinite inertia, and therefore, a series suspension, e.g., where electromagnetic actuation is represented by a rotary motor connected to a ball screw bearing, is preferable. These direct-drive electromagnetic systems are more suited to a parallel suspension, where the inertia of the actuator is minimized.

Recently, a system has been presented, namely, the Bose suspension system [11], as shown in Fig. 3, which includes a linear electromagnetic motor and a power amplifier at each wheel, and a set of control algorithms. In this system, the high-bandwidth linear electromagnetic motor is installed at each wheel. This linear electromagnetic motor responds quickly enough to counter the effects of bumps and potholes while maintaining a comfortable ride. Additionally, the motor has been designed for maximum strength in a small package, allowing it to put out enough force to prevent the car from rolling and pitching during

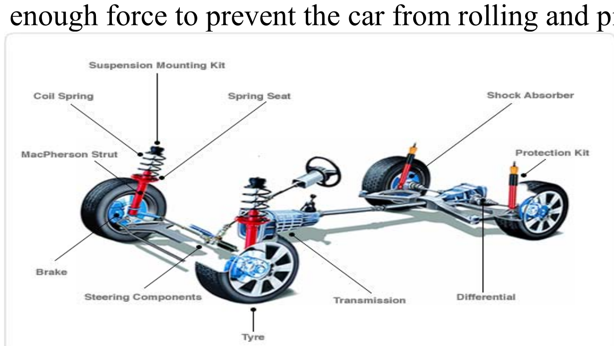

Fig. 3. Bose suspension system.

aggressive driving maneuvers. Electrical power is delivered to the motor by a power amplifier in response to signals from the control algorithms. The bidirectional power amplifier allows power to flow into the linear electromagnetic motor and allows power to be returned from the motor. For example, when the suspension encounters a pothole, power is used to extend the motor and isolate the vehicle's occupants from the disturbance. On the far side of the pothole, the motor operates as a generator and returns the power back through the amplifier. It is attained that this suspension system requires less than a third of the power of a typical vehicle's air-conditioning system, i.e., hundreds of watts. Compared with hydraulic actuators, the main advantages of electromagnetic actuators are as follows:

1) Increased efficiency;
2) Improved dynamic behavior;
3) Stability improvement;
4) Accurate force control;
5) Dual operation of the actuator.

The disadvantages are as follows:

1) increased volume of the suspension, since the force density of the active part of hydraulics is higher than for electromagnetic actuation, i.e., system mass and volume could be less;
2) Relatively high current for a 12- to 14-V system;
3) Conventional designs that need excitation to provide a continuous force;
4) Higher system costs.

Although numerous linear motor topologies exist, the permanent-magnet (PM) synchronous linear actuator is investigated since it offers a high permissible power density at an ever-decreasing cost penalty. More specifically, a tubular PM synchronous actuator, as shown in Fig. 1(b), is preferred since this actuator inhibits the highest force density, where various different topologies are

a) Ironless (no attraction forces);
b) Ironless with back-iron, higher force density compared with (a);
c) Slotted with soft magnetic powder composite materials (low saturation level);
d) laminated (difficult to achieve but higher dynamic capability).

The actuator topology achieving the highest force density is (d); however, (b) is more preferred with regard to manufacturing.

Various magnetization patterns are possible, such as

1) Radically magnetized north and south poles;
2) Axially magnetized north and south poles with iron poles (no back-iron);
3) Halbach array (no back-iron).

In [7], a slot less tubular actuator is optimized for the mean output force for all these magnetization patterns and for interior (moving magnet) and exterior (moving coil) magnet topologies. It has been shown that exterior Halbach magnetization offers the highest output force within the volume constraints given by the BMW 530i. Equivalent conclusions were drawn for the slotted topology in [22]; however, a higher force density is obtained than in [7].

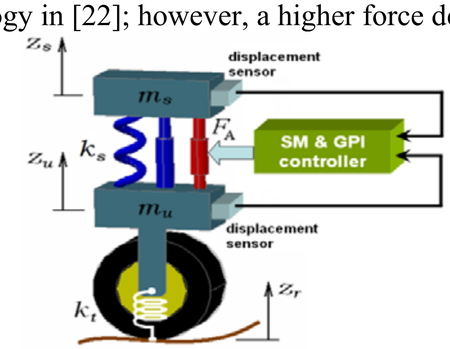

Fig. 4. Quarter car model, including body disturbances and active suspension.

TABLE I
NOMINAL PARAMETERS OF THE QUARTER CAR MODEL

Parameter	Value	Description
k	30 kN/m	Passive spring stiffness
k_w	160 kN/m	Tire stiffness
d	1200 Ns/m	Passive damping constant
m_b	450 kg	Quarter sprung mass
m_w	40 kg	Unsprung mass

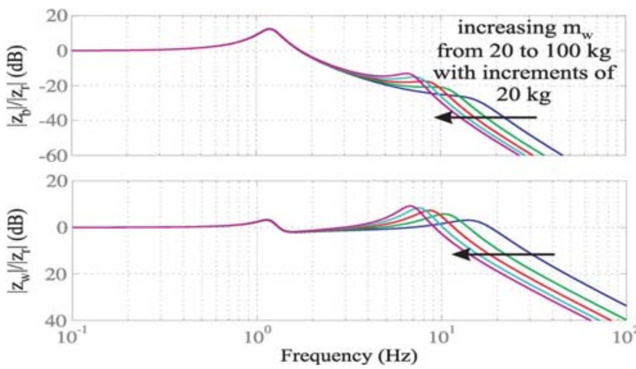

Fig. 5. Bode diagrams of the sprung and unsprung mass responses to road disturbances for increasing unsprung mass.

IV. SYSTEM MODELING

In general, a full car model [23] is preferred to model the dynamic behavior of the suspension system; however, roll and pitch behavior can also be modeled as an equivalent disturbance force acting on the body mass, i.e., *F*body. Hence, for the scope of this paper, a quarter car model, as shown in Fig. 4, is used with the parameters shown in Table I. This model allows, for example, the investigation of the increase or decrease in the respective sprung and unsprung masses on the response of body height *zb* and wheel height *zw* to road disturbances *zr*. From these Bode diagrams, it can be observed that increasing the unsprung mass, as shown in Fig. 5 (for a wheel motor design [3], [4]), and decreasing the sprung mass, as shown in Fig. 6 (the more electrical car), or increasing the unsprung-to-sprung mass ratio, leads to an increase in response of the frequency range

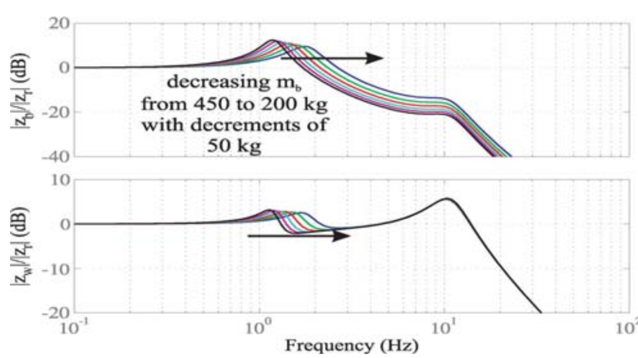

Fig. 6. Bode diagrams of the sprung and unsprung mass responses to road disturbances for decreasing sprung mass.

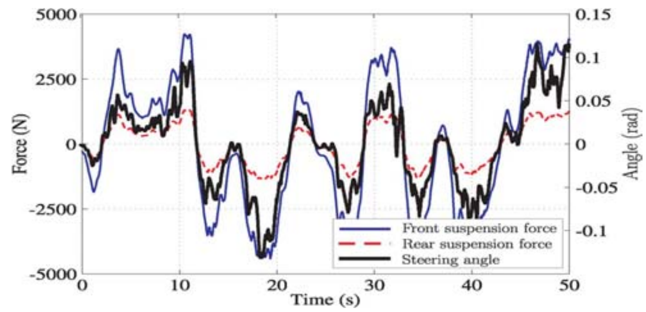

Fig. 7. Time interval of the derived suspension forces from acceleration measurements on the Nürburgring, together with the steering angle.

between 2 and 10 Hz, which decreases the isolation of road disturbances and comfort, as explained in Section II. Hence, the suspension system should be designed for maximum sprung-to-unsprung mass ratio while minimizing total mass.

V. SYSTEM SPECIFICATIONS

A. Roll and Pitch Behavior

During high-speed cornering, braking, and accelerating, roll and pitch forces tend to turn the body around the roll and pitch axes. As a result, the total weight is not evenly distributed along the four wheels, which increases the instability and could lead to tip over of the vehicle during cornering [24]. To have an indication of the particular roll forces during high-speed cornering, a test drive with a BMW 530i is performed on the Nürburgring in Germany. The vertical acceleration of the sprung mass is measured, and the resulting roll forces are calculated; an extensive analysis is given in [7]. A time interval of the calculated forces deducted from the measurements, together with the steering angle, is shown in Fig. 7. During calculation, a front-to-total force ratio of 0.7 is taken into account to design for safer under steer behavior. It can be observed that a peak force of 4 kN is necessary for the front actuators. Furthermore,

Fig. 8. Sizes of the bump on the test track.

TABLE II
STROKE AND SPEED MEASUREMENT RESULTS

	Max. bound	Max. rebound	Mean bound	Mean rebound
Stroke	80 mm	58 mm	4.5 mm	3.4 mm
Speed	1.28 m/s	2.25 m/s	38.5 mm/s	38.4 mm/s

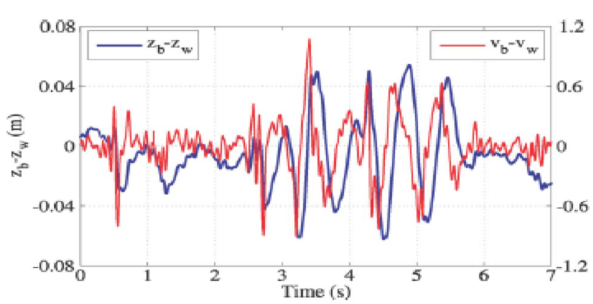

Fig. 9. Position ($zb - zw$) and speed ($vb - vw$) measurements while driving on the bump of Fig. 8.

a mean force of 2 kN is measured; however, to determine the mean force specification, a duty cycle has to be taken into account since the Nürburgring does not represent normal driving and road conditions.

B. Road Disturbances

A further test drive is performed on a more common road with bumps and potholes. During this measurement, the relative vertical position between the sprung and the unsprung mass is measured with an optical sensor. This sensor is aligned with the passive spring and damper; hence, the stroke is directly measured. The speed is then derived, where a small time interval is shown in Fig. 9, where, at that moment (2.5 s), the bump, as shown in Fig. 8, is hit at 35 km/h. From these measurements, the stroke, speed, and force requirements of the suspension system can be derived, which are given in Table II. However, first, the characteristics of the passive spring, including the bump stop and damper, need to be measured, e.g., using a standard Verband Der Automobile industry (VDA) test. This measurement is supplemented with additional points, as the maximum velocity in the VDA test is limited to 1.05 m/s. Although this limit is sufficient for normal road behavior, when very steep bumps are hit, as shown in Fig. 9, the velocity increases beyond this point. The measured spring and damper characteristics are shown in Figs. 10 and 11, respectively. Using the on road speed measurement and the off-road measured damping characteristic, the absorbed power of the hydraulic damper can be calculated. An instantaneous peak damping power of 2 kW is necessary when driving onto the bump shown in Fig. 8; however, when taking the average value of the total driving cycle, only a power level of 16 W per damper is necessary, which is comparable with the results obtained in [25] for normal city driving. Comparable with the results obtained in [25] for normal city driving.

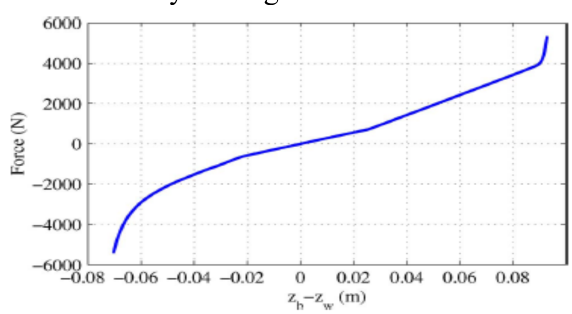

Fig. 10. Measured spring characteristic of the passive suspension.

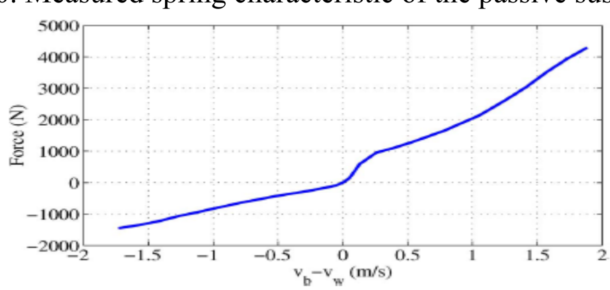

Fig. 11. Measured damper characteristic of the passive suspension.

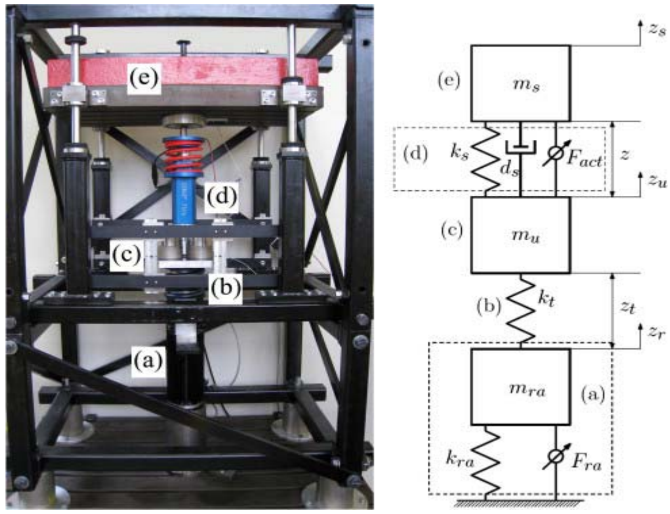

Fig. 12. Quarter car test setup.

VI. QUARTER CAR SETUP

In this section, the on-road measurements will be reproduced by means of electromagnetic actuation on a quarter car test setup shown in Fig. 12. The setup consists of a single moving mass (hence, wheel dynamics are neglected), together with the passive suspension of a BMW 530i, and a three-phase brushless TPMA in parallel (on top of the quarter car setup).

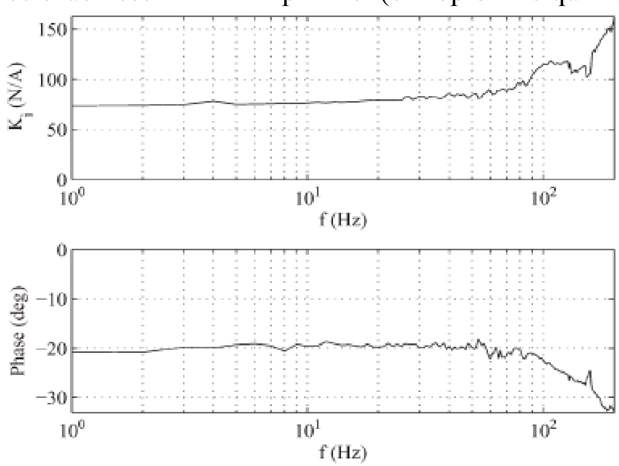

Fig. 13. Bode diagram of the motor constant of the TPMA.

A. TPMA

One of the advantages of an electromagnetic actuator compared with a hydraulic actuator is the increased bandwidth. In Fig. 13, the Bode diagram of the motor constant of the TPMA is shown; this test is performed while applying a sinusoidal nominal current (corresponding to a nominal force of 1 kN and a motor constant of 75 N/A), with increasing frequency to the locked TPMA. It can be observed that the bandwidth of the actuator is higher than 50 Hz, proving the improved dynamic force capability compared with a hydraulic system. The measurement results for higher frequencies (> 100 Hz) are inaccurate since resonance frequencies of the total setup are becoming dominant. The phase shift of −20◦ at lower frequencies is caused by nonlinearities of the setup and hysteresis of the force sensor.

B. Controller

The position of the body mass of 450 kg, i.e, *mb*, is measured with an incremental encoder and controlled with a reference position equal to the on-road measurement shown in Fig. 9. A feed forward controller, which uses the measured spring and damper characteristics of Fig. 10 and 11, respectively, is employed. Furthermore, a feedback controller ensures correct tracking of the reference and compensates the friction and cogging forces of the actuator and the setup, as shown in the block scheme of Fig. 14. The feedback controller, with an open loop bandwidth of 15 Hz, is designed using a model-based approach [26] on a measured frequency response function of the quarter car setup given in Fig. 15. It consists of a notch filter at 138 Hz, a low-pass filter (50 Hz), and a lead filter (zero at 5 Hz and pole at 45 Hz) given by

$$C_{\text{fb}} = K_p C_{\text{notch}} C_{\text{LP}} C_{\text{lead}} \quad (1)$$

$$K_p = 20\,000 \quad (2)$$

$$C_{\text{notch}} = \frac{1.33e^{-6}s^2 + 230.7e^{-6}s + 1}{1.33e^{-6}s^2 + 1.153e^{-3}s + 1} \quad (3)$$

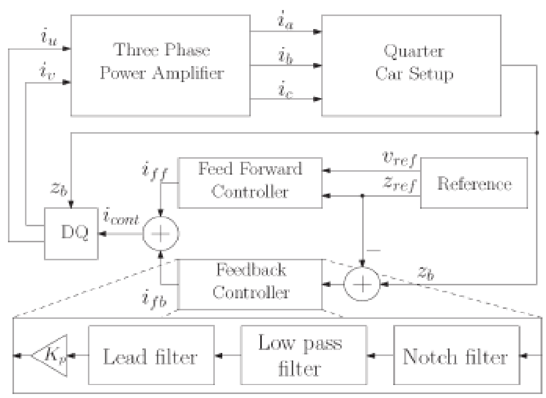

Fig. 14. Block diagram of the measurement setup.

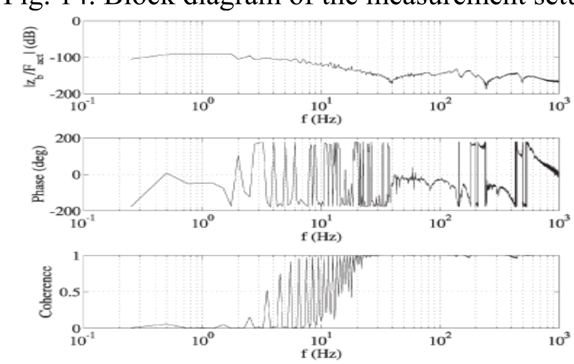

Fig. 15. System identification of the quarter car test setup.

$$C_{\text{LP}} = \frac{1}{3.183e^{-3}s + 1} \quad (4)$$

$$C_{\text{lead}} = \frac{31.83e^{-3}s + 1}{3.537e^{-3}s + 1}. \quad (5)$$

If correct tracking is obtained, the actuator should apply equal force levels, as compared with the passive suspension during the test drive. The tracking of the actuator, as shown in Fig. 16, gives an indication of the dynamic possibilities of electromagnetic actuation. The electromagnetic actuator has the possibility of applying forces equivalent to the passive suspension system within a very small response time.

VII. CONCLUSION

Due to the change in vehicle concepts to the more electric car, the suspension system becomes ever more important due to changes in the sprung and unsprung masses. Active electromagnetic suspension systems can maintain the required stability and comfort due to the ability of adaptation in correspondence with

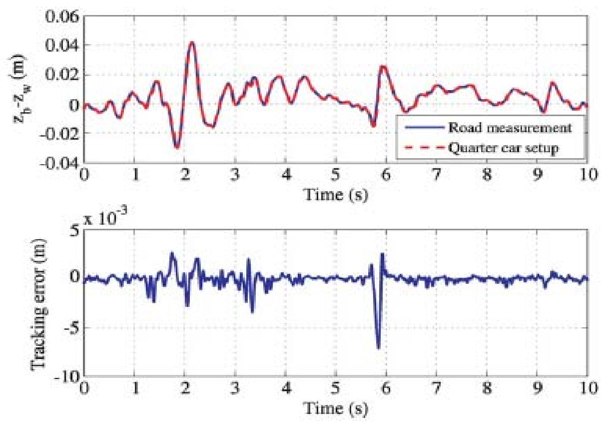

Fig. 16. Time interval of the on-road measurements and off-road electromagnetic actuation on the quarter car test setup.

the state of the vehicle. Specifications are drawn from on- and off-road measurements on a passive suspension system, and it can be concluded that, for ARC, a peak force of 4 kN and an RMS force of 2 kN (duty cycle of 100%) are necessary for the front actuators. Furthermore, the necessary peak damping power is around 2 kW; however, the RMS damping power is only 16 W during normal city driving. The maximum bound and rebound strokes are 80 and 58 mm, respectively. The on-road measurements, which are mimicked on a quarter car setup by means of electromagnetic actuation, a good tracking response, and measurement of the frequency response of the tubular actuator, prove the dynamic performance of the electromagnetic suspension system.

REFERENCES

[1] D. N. Wormley, K. M. Bauer, and J. E. Bernard, “An assessment of the National Highway Traffic Safety Administration’s rating system for rollover resistance,” Transp. Res. Board, Special Rep. 265, 2002.
[2] *Electric Cars Europe*. [Online]. Available: http://www.ececars.nl/
[3] K. Cakir and A. Sabanovic, “In-wheel motor design for electric vehicles,” in *Proc. 9th IEEE Int. Workshop Adv. Motion Control*, 2006, pp. 613–618.
[4] S. Zetterstromi, “Electromechanical steering, suspension, drive and brake modules,” in *Proc. 56th IEEE VTC*, 2002, vol. 3, pp. 1856–1863.
[5] J. J. H. Paulides, L. Encica, E. A. Lomonovai, and A. J. A. Vandienputi, “Design considerations for a semi-active electromagnetic suspension system,” *IEEE Trans. Magni.*, vol. 42, no. 10, pp. 3446–3448, Oct. 2006.
[6] J. Wang, W. Wang, K. Atallah, and D. Howe, “Comparative studies of linear permanent magnet motor topologies for active vehicle suspension,” in *Proc. IEEE VPPC*, Sep. 2008, pp. 1–6.

[7] B. L. J. Gysen, J. L. G. Janssen, J. J. H. Paulides, and E. A. Lomonova, “Design aspects of an active electromagnetic suspension system for automotive applications,” *IEEE Trans. Ind. Appl.*, vol. 45, no. 5, pp. 1589–1597, Sep./Oct. 2009.
[8] A. J. Benson, “Motion sickness,” in *Encyclopedia of Occupational Health and Safety*, J.M. Stellman, Ed., 4th ed. Geneva, Switzerland: Int. Labour Office, 1998.
[9] G. R. Barnes and B. H. Rance, “Head movement induced by angular oscillation of the body in the pitch and roll axes,” *Aviat. Space Environ Med.*, vol. 46, no. 8, pp. 987–993, Aug. 1975.
[10] M. Strassberger and J. Guldner, “BMW’s dynamic drive: An active stabilizer bar system,” *IEEE Control Syst. Mag.*, vol. 24, no. 4, pp. 28–29, Aug. 2004, 107.
[11] W. D. Jones, “Easy ride: Bose Corp. uses speaker technology to give cars adaptive suspension,” *IEEE Spectr.*, vol. 42, no. 5, pp. 12–14, May 2005.
[12] L. J. Smart, T. A. Stoffregen, and B. G. Bardy, “Visually induced motion sickness predicted by postural instability,” *Hum. Factors*, vol. 44, no. 3, pp. 451–465, 2002.
[13] L. H. Frank, J. G. Casali, and W. W. Wierwille, “Effects of visual display and motion system delays on operator performance and uneasiness in a driving simulator,” *Hum. Factors*, vol. 30, no. 2, pp. 201–217, Apr. 1988.
[14] E. C. Regan and K. R. Price, “The frequency of occurrence and severity of side-effects of immersion virtual reality,” *Aviat. Space Environ. Med.*, vol. 65, no. 6, pp. 527–530, Jun. 1994.
[15] Y. Yoo, G. C. H. Lee, and S. A. Jones, “Vection, compensatory sway, and simulator sickness,” in *Advances in Occupational Ergonomics and Safety*, B. Dos and W. Karowski, Eds. Amsterdam, The Netherlands: IOS, 1997, pp. 589–592.
[16] P. M. Gahlinger, “Motion sickness—How to help your patients avoid travel travail,” *Postgrad. Med.*, vol. 106, no. 4, pp. 177–184, Oct. 1999.
[17] J. R. Lackner, “Motion sickness,” in *Encyclopedia of Neuroscience*, G. Adelman and B. Smith, Eds., 3rd ed. Amsterdam, The Netherlands: Elsevier, 2003.
[18] I. Martins, J. Esteves, G. D. Marques, and F. P. da Silva, “Permanent-magnets linear actuators applicability in automobile active suspensions,” *IEEE Trans. Veh. Technol.*, vol. 55, no. 1, pp. 86–94, Jan. 2006.
[19] S. Zhao and Y. Li, “Multi-sensor information fusion and strong tracking filter for vehicle nonlinear state estimation,” in *Proc. IEEE Intell. Vehicles Symp.*, Jun. 2009, pp. 747–751. [20] J. Sijs, Z. Papp, and P. van den Bosch, “Vehicle motion-state-estimation using distributed sensing,” in *Proc. IEEE Intell. Vehicles Symp.*Jun. 2008, pp. 458–463.
[21] *Sachs ABC Module*. [Online]. Available: http://www.zfsachs.com
[22] B. Gysen, J. Paulides, L. Encica, and E. Lomonova, “Slotted tubular permanent magnet actuator for active suspension systems,” in *Proc. LDIA*, Sep. 2009, pp. 292–295. [23] A. Kruczek and A. Stribrsky, “A full-car model for active suspension— Some practical aspects,” in *Proc. IEEE ICM*, 2004, pp. 41–45.
[24] R. Cross, “Role of centrifugal force in vehicle roll,” *Amer. J. Phys.*, vol. 67, no. 5, pp. 447–448, 1998.
[25] P. Hsu, “Power recovery property of electrical active suspension systems,” in *Proc. 31st IECEC*, Aug. 1996, vol. 3, pp. 1899–1904.
[26] G. F. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems*. Englewood Cliffs, NJ: Prentice-Hall, 2006.