Turnitin Originality Report

Processed on: 14-Dec-2022 10:49 +03
ID: 1980957093
Word Count: 4040
Submitted: 1

Draft1 By Kutlay Hanli

Similarity Index	Similarity by Source	
20%	Internet Sources:	16%
	Publications:	8%
	Student Papers:	4%

9% match (Internet from 26-Mar-2019)
http://fuel-bmstu.ru/wp-content/uploads/2018/05/Effects-of-structure-parameters-on-the-static-electromagnetic-characteristics-of-high-speed-solenoid-valves.pdf

2% match (Internet from 02-Dec-2020)
https://www.hindawi.com/journals/mpe/2014/293637/

2% match (student papers from 23-Oct-2020)
Submitted to Coventry University on 2020-10-23

1% match (Meisheng Yang, Junhui Zhang, Bing Xu, Wei Wang. "Study on electromagnetic force of the new micro digital valve", Microsystem Technologies, 2018)
Meisheng Yang, Junhui Zhang, Bing Xu, Wei Wang. "Study on electromagnetic force of the new micro digital valve", Microsystem Technologies, 2018

< 1% match (Internet from 05-Jun-2020)
http://www.scielo.org.za/pdf/sajie/v30n2/06.pdf

< 1% match (student papers from 11-Sep-2015)
Submitted to Edison State College on 2015-09-11

< 1% match ()
Zaini. "Control strategies for blended braking in road vehicles. A study of control strategies for blended friction and regenerative braking in road vehicles based on maximising energy recovery while always meeting the driver demand.", School of Engineering Design and Technology, 2012

< 1% match (student papers from 31-Aug-2022)
Submitted to Malta College of Arts,Science and Technology on 2022-08-31

< 1% match (Paolo Lino, Guido Maione. "Accurate dynamic modeling of an electronically controlled CNG injection system", IFAC-PapersOnLine, 2016)
Paolo Lino, Guido Maione. "Accurate dynamic modeling of an electronically controlled CNG injection system", IFAC-PapersOnLine, 2016

< 1% match (student papers from 16-Sep-2014)
Submitted to North West University on 2014-09-16

< 1% match (Guillermo Hauke. "A segregated method for compressible flow computation. Part II: general divariant compressible flows", International Journal for Numerical Methods in Fluids, 09/20/2005)
Guillermo Hauke. "A segregated method for compressible flow computation. Part II: general divariant compressible flows", International Journal for

Numerical Methods in Fluids, 09/20/2005

< 1% match (student papers from 29-Aug-2013)
Submitted to University of Strathclyde on 2013-08-29

< 1% match (Internet from 16-Jul-2020)
http://docplayer.net/48896414-Journal-of-concrete-and-applicable-mathematics.html

< 1% match (Internet from 03-Jul-2016)
http://homepages.math.uic.edu/~hanson/pub/Slides/bk0allfinal.pdf

< 1% match (Internet from 27-Apr-2020)
https://studylib.net/doc/18665512/get-cached-pdf

< 1% match (Meisheng Yang, Junhui Zhang, Bing Xu. "Experimental Study and Simulation Analysis on Electromagnetic Characteristics and Dynamic Response of a New Miniature Digital Valve", Advances in Materials Science and Engineering, 2018)
Meisheng Yang, Junhui Zhang, Bing Xu. "Experimental Study and Simulation Analysis on Electromagnetic Characteristics and Dynamic Response of a New Miniature Digital Valve", Advances in Materials Science and Engineering, 2018

< 1% match (Xia Wang, Yuefen Chen, Shengqiang Liu, Xinyu Song. "A class of delayed virus dynamics models with multiple target cells", Computational and Applied Mathematics, 2013)
Xia Wang, Yuefen Chen, Shengqiang Liu, Xinyu Song. "A class of delayed virus dynamics models with multiple target cells", Computational and Applied Mathematics, 2013

< 1% match (S.V. Angadi, R.L. Jackson, Song-Yul Choe, G.T. Flowers, J.C. Suhling, Young-Kwon Chang, Jung-Keol Ham. "Reliability and life study of hydraulic solenoid valve. Part 1: A multi-physics finite element model", Engineering Failure Analysis, 2009)
S.V. Angadi, R.L. Jackson, Song-Yul Choe, G.T. Flowers, J.C. Suhling, Young-Kwon Chang, Jung-Keol Ham. "Reliability and life study of hydraulic solenoid valve. Part 1: A multi-physics finite element model", Engineering Failure Analysis, 2009

< 1% match (publications)
International Journal of Productivity and Performance Management, Volume 55, Issue 3 (2006-09-19)

< 1% match (Mathematical Engineering, 2015.)
Mathematical Engineering, 2015.

 vii Chapter 1: Introduction Chapter 1 INTRODUCTION This thesis derives the mechanical, fluid and electromagnetic model of a solenoid valve from the structural parameters. TODO: write abstract Chapter 2 MAGNETO MOTIVE FORCE Magneto motive force is force that allows solenoid valves to open using the linear motion of an armature. Magneto motive force is a function of magnetic flux , surface area perpendicular to the magnetic flux acting on armature S2 and magnetic reluctance of vacuum or material filling range of linear motion µ0. Fmag = 2 · µ0 · S2 1 · 2 (2.1) 2.1 Magnetic Flux Magnetic flux through the magnetic circuit of a valve is a function of coil turns N, current through the coil I, and total magnetic reluctance of the magnetic circuit Rtotal. = N · I Rtotal (2.2) N is constrained by the geometry of the valve, there is a limit on how many turns one can add for a given cross sectional area. I is constrained by the wire current carrying capacity. In further section we will analyze the e↵ect of wire diameter and valve geometry on magnetic flux and magneto motive force. 2.1.1 Magnetic Reluctance Magnetic reluctance R of a simple 430F stainless steel block can be computed as: R = l (2.3) µ0µrA where l is length of the magnetic path in meters, µ0 is permeability of free space (vacuum) 4⇡ · 10 7H/m, µr is relative permeability of a magnetic material (850 for 430F SS) and A is the cross sectional area in m2. [Zhao et al., 2017] Zhao et al. Figure 2.1: Magnetic flux through a simple bar Figure 2.2: The structural schematic of the HSV [Zhao et al., 2017] studied the e↵ect of structural parameters of a solenoid system with the model: Zhao et al. computed the total magnetic reluctance through the green arrows thus they computed the magnetic flux and magneto motive force. Researchers validated their static electromagnetic force model by running experiments on a test bench where they fixed the armature and the force sensor at one end and placed the iron core free on the other end 2.3. They present the e↵ects of driving current on electromagnetic energy conversion in fig. 2.4. "When I increases from 1A to 18A, the electromagnetic force first increases rapidly , @F/@I reaches a maximum value at a driving current of 4A, and then decreases. When I < 4A, with increasing I, the increase of the Figure 2.3: Comparison between simulated and experimental results of the electro- magnetic force [Zhao et al., 2017] Figure 2.4: Influence of the driving current on the electromagnetic force increment at di↵erent working air gaps [Zhao et al., 2017] electromagnetic force at the air gap of 0.1mm always greater than that at the air gap of 0.12mm. When I > 4A, the two curves nearly overlap, and the increment of the electromagnetic force with increasing I gradually decreases. The phenomena can be explained with the B-H curve of the iron core and armature." [Zhao et al., 2017] As seen in fig. 2.5, change @R/@I starts to dominate the total magnetic reluctance. The researchers conclude that "increasing I will cause premature saturation in the Figure 2.5: Influence of driving current on total magnetic reluctance at di↵erent working air gaps [Zhao et al., 2017] HSV, and the magnetic reluctance of the soft magnetic material will become a decisive factor in restricting the variation of the total magnetic reluctance, which causes the changes of the total magnetic reluctance at di↵erent working air gaps to be the same with increasing I. Therefore, it can be surmised that when I > 4A, the electromagnetic forces with di↵erent working air gaps will increase at the same rate with increasing I."[Zhao et al., 2017] The fig 2.6 show us the B-H curve and Figure 2.6: The B-H curve of the iron core and armature. [Zhao et al., 2017] it shows how magnetic saturation occurs. To increase the materials magnetic flux density one must exponentially increase the magnetic field intensity which results in high power consumption or is limited by solenoids current carrying capacity. "I and the working air gap both have significant e↵ects on the variation of the total magnetic reluctance. Too large current or small working air gap will lead to the saturation of magnetic circuit." [Zhao et al., 2017] For an e cient solenoid system the air gap should have the highest magnetic reluctance contribution to the total magnetic reluctance. “Fig 2.7 shows that at di↵erent values of I, the electromagnetic Figure 2.7: Influence of h on the electromagnetic force at di↵erent driving currents [Zhao et al., 2017] (x axis is in 10mm) force decreases with an increasing of the working air gap, and the rate of decrease is a↵ected by the value of I. The larger I becomes, the smaller the rate is.” [Zhao et al., 2017] This occurs because the magnetic reluctance caused by saturation is dominates the magnetic reluctance due to the air gap. The fig. 2.8 “shows that at di↵erent values of I, the total magnetic reluctance increases with an increase of the working air gap. When the total magnetic flux is constant, the electromagnetic force decreases with increasing total magnetic reluctance. If I is small, the capability of electromagnetic energy conversion in the HSV will be significantly influenced by the working air gap. But if I is large enough to lead to the magnetic saturation, the working air-gap has only a minor influence.” [Zhao et al., 2017] Figure 2. 8: Influence of h on the total magnetic reluctance at di↵erent driving currents [Zhao et al., 2017] (x axis is in 10mm) 2.1.2 N · I (Ampere Turns) Figure 2.9: Electromagnetic force of di↵erent Ampere-turns [Yang et al., 2019] As seen in eq. 2.1, magneto motive force is linearly proportional to N · I . There is however a limit to this relationship. In fig. 2.9 Yang et al. shows that magneto motive force is saturated. It should be noted that for di↵erent air gaps (range of linear motion) the saturation level varies. Di↵erent air gap distances result in exponential increase in air gap magnetic reluctance. thus it requires more ampere turns to increase the magnetic reluctance of the magnetic circuit to match and exceed the air gap. 2.2 Armature Surface Area Armature surface area perpendicular to the magnetic flux acting on it is crucial in determining magneto motive force as seen in eq. 2.1. Yang et al. improved the e ciency of a micro digital valve by changing the design in such a way that they increased the armature surface area which led to an increase in magnetic flux thus increasing the magneto motive force for the same N · I [Yang et al., 2019]. ”Under Figure 2.10: Traditional micro high-speed digital valve [Yang et al., 2019] the same displacement of the iron core, the testing results of electromagnetic force Figure 2.11: Novel micro high-speed digital valve [Yang et al., 2019] of the novel micro high-speed digital valve were about 1.33 times as that of the traditional valve. ... ratio of the testing results was in good agreement with the area ratio of the two valves.” [Yang et al., 2019] Figure 2.12: Electromagnetic force for di↵erent arrangement [Yang et al., 2019] Chapter 3 MAGNETIC MODEL OF A SOLENOID VALVE In this section we will be modelling the magnetic circuit of the HSV by Yang et al. in the previous chapter. As seen in Fig. 3.1, magnetic circuit is divided in to 4 Figure 3.1: Magnetic path shown on assembly linear sections following the method of Zhao et al. P ath1 is uninterrupted and flows through the part labeled as magnetic top. Rpath1 = 4 rCout μ μ0 tmta ⇡ (ca + cr + 2 rCout + tshell) (3.1) Path 2 is divided in to 3 sections. P ath2a is the outer vertical path through the Figure 3.2: Detail view on vertical air gap between magnetic top and shell. magnetic top. P ath2b is the vertical path through the ine↵ective air gap due to axial clearance between shell and magnetic top shown in Fig. 3.2. P ath2c is the path through shell. Rpath2 = μ0 ⇡ (cr + rCout + tshell)2 (cr + rCout)2 ca + hC ca + 2 tcfa + tm2ba + tmta (3.2) μ μ0 ⇡ (cr + rCout + tshell)2 (cr + rCout)2 Path 3 is divided in to 5 sections. P ath3a is the horizontal path through shell. P ath3b is the path through ine↵ective air gap due to radial clearance between shell and magnetic bottom shown in Fig. 3.3. P ath3c is the horizontal path through magnetic bottom. P ath3d is the path through ine↵ective air gap due to radial clearance between shell and magnetic bottom shown in Fig. 3.4. P ath3e is the horizontal path through the armature. Rpath3 = 2 μ μ0 tmba ⇡ + cr μ0 tmba ⇡ c2r + rA + cr μ0 tmba ⇡ c2r + rCout + (3.3) tshell 2 μ μ0 tmba ⇡ cr + rCout + tsh2ell 2 (cr + rA rCout) μ μ0 tmba ⇡ (cr + rA + rCout) Path 4 is divided in to 3 sections. P ath4a is the vertical path through the armature. Figure 3.3: Detail view on horizontal air gap between shell and magnetic bottom. Figure 3.4: Detail view on horizontal air gap between magnetic bottom and arma- ture. P ath4b is the path through the e↵ective air gap shown in Fig. 3.5 where the use full magneto motive force is generated. P ath4b is the vertical path through magnetic top. The e↵ective air gap P ath4b is further divided in to 2 sections. P ath4b1 is where opposing faces are horizontal and the magnetic flux through is vertical, therefore the Figure 3.5: Detail view on vertical e↵ective air gap between magnetic top and ar- mature. magnetic reluctance of P ath4b1 is: RPath4b1 = µ0rcham2⇡ hair (3.4) Computing P ath4b1 is trickier. First we compute ✓ = atan hcham (3.5) ✓rA rcham◆ hchamferAirgap = hair cos(✓) (3.6) and then we assumed that Achamfer = ⇡ rA2 rcham2 (3.7) When we apply the eq. 2.3 we compute P ath4b2 as the following: RPath4b2 = hair µ0⇡(rA2 rcham2) (rAhchracmha2m)2 +1 (3.8) Total e↵ective reluctance P ath4b is⇣ computed wit⌘h the following assumption for parallel magnetic flux in eq 3.9 1 = 1 + 1 1 Rcombined R1 + · · · + (3.9) R2 Rn 1 1 Rcombined RP ath4b1 RP ath4b2 = + 1 (3.10) P ath4b is computed and simplified in eq. 3.11. Rcombined = 1 1 1 RP ath4b1 RP ath4b2 + = 1 ⇡ µ0 rcham2 ⇡ µ0 (rA2 rcham2) hcham2 2 +1 (3.11) hair + ✓ (rA rcham) ◆ hair = hair (rA rcham) µ0 ⇡ hcham2 rA + rcham hcham2 + rA3 rcham rA2 RP ath4 = ca + h2C µ µh0airrA+2 ⇡tcfa + tm2ba + hair (rA rcham) µ0 ⇡ hcham2 rA + rcham hcham2 + rA3 rcham rA2 + (3.12) ca + h2C + tcfa + tm2ta µ µ0 rA2 ⇡ Rtotal = RP ath1 + RP ath2 + RP ath3 + RP ath4 (3.13) After computing the total reluctance we can compute the magnetic flux using the eq. 2.2 and the magneto motive force using the eq. 2.1. Chapter 4 DYNAMIC MODEL OF A SOLENOID VALVE 4.1 Mechanical Model The only moving part in this direct acting solenoid part is the armature. The normally closed solenoid valve is turned on and o↵ via applying a voltage on the solenoid leads that creates the magneto motive force and lets the fluid flow through. In fig. 4.1 we present the forces acting on the armature. Fmm is the magneto motive force, Fairgap is the force generated by the fluid pressure in the air gap on the top surface of the armature, Fchamber is the generated by the fluid pressure in the chamber on the bottom surface of the armature and Fspring is the force generated by the compression spring. This free body diagrams describes the dynamic behaviour of the valve. In section 2 we showed how to compute Fmm for a given design, armature Figure 4.1: Armature Free Body Diagram position and applied current. 1 · 2 Fmm = 2 · µ0 · S2 (2.1) Fairgap = ⇡ rA2 Pairgap (4.1) Fchamber = ⇡ rA2 Pchamber (4.2) Fspring = (x + x0) ⇥ ks (4.3) where x0 stands for the pre-loading of the spring and ks is the spring constant F (t) = Fmm(t) Fairgap(t) + Fchamber(t) Fspring(t) (4.4) F (t) = m ẍ(t) (4.5) ẋ(t) = ẋ(t 1) + ẍ(t 1) dt (4.6) x(t) = x(t 1) + ẋ(t 1) dt + ẍ(t 1) dt2 (4.7) The mass of the armature can be computed from the material density (430F SS for this model) ⇢ and the armature geometry. m = rA2 ⇢ hC 2 + tcfa (4.8) ✓ ◆ 4.2 Electrical Model Figure 4.2: Schematic of electrical circuit. (left) Valve powered o↵. (right) Valve powered on. In fig. 4.2 the electrical schematic of the valve is presented. A solid state relay (SSR) is used to switch the solenoid on and o↵ and any losses due to wiring and SSR is ignored in the model. We can represent the schematic with the following equations: Vdd = VL + VR (4.9) = L di + R i Vdd = L(t) dt (t) + R i(t) di (4.10) Assuming Vdd is constant we can compute ddit with the following derivation: VL(t) = Vdd Ri(t) (4.11) di VL(t) dt(t) = L(t) (4.12) We can compute the inductance of the solenoid system using the eq. 4.13. Induc- tance will play a crucial role in the dynamic analysis of the solenoid valve. Inductance will dictate the reaction time of the solenoid valve. L = N i = N 2 Rtotal (4.13) We can compute the resistance R from coil geometry (RCin coil inner radius, RCout coil outer radius), winding number N, wire diameter dw and electrical resistivity of the conductor ⇢ as follows: R = ⇡ (rCout + rCin) N ⇢ (4.14) Finally we can compute i(t) with the follwing equation: i(t) = i(t 1) + dt (t 1) dt di (4.15) Notice in fig. 4.2 that the circuit is a LR circuit. Valve reaction time is an important Figure 4.3: (a) An RL circuit with a switch to turn current on and o↩. When in po- sition 1, the battery, resistor, and inductor are in series and a current is established. In position 2, the battery is removed and the current eventually stops because of energy loss in the resistor. (b) A graph of current growth versus time when the switch is moved to position 1. (c) A graph of current decay when the switch is moved to position 2.[OpenStax, 2022] performance metric for solenoid valves. Generally it is assumed that 3⊠ is the time that the valve is fully opened. Valve closing time on the other hand depends on the spring constant ks and pressure balance between chamber and air gap. This will be discussed in the next section ⊠ = L R (4.16) Notice in eq. 4.13 inductance varies with magnetic flux, thus varies by Rtotal. This results in di↩erent time constants for di↩erent armature positions. For this dynamic model, a positive voltage will be applied for 1.2 ⊠opening seconds. After this duration the voltage will be removed and the simulation will be run for another 1.2 ⊠closing seconds. ⊠opening = L(hair) R (4.17) ⊠opening = L(ca) R (4.18) In eq. 4.17 the inductance is computed with the maximum air gap and in eq. 4.18 the inductance is computed with minimum air gap that is equal to the axial clearance ca. 4.3 Simulation Meta Data Simulation time step is set to 10ns, 10 8s, in order to account for the dynamic nature of the simulation. As it is presented in the next section, mass flows and the change in pressures and temperatures are integrated through the simulation. A small time step is required to keep the simulation stable. For step sizes above 1us the simulation diverges due to small control volumes and high flow rates. 4.4 Flow Model The valve design has 2 control volumes. These control volumes are Vairgap and Vchamber. The states of these volumes are defined by their volume V , temperature T, density ⤏ and mass M. The interaction between these control volumes are defined by the armature radial clearance flow path. This flow path is defined by a flow cross section area Arc and a discharge coe cient Cd,rc. The valve is placed between two reservoirs, upstream and downstream. For this model the upstream and downstream reservoirs are assumed to be infinite and have constant temperature and density. The interaction between the chamber and the reservoirs are defined by inlet and outlet orifices. These orifices are defined by rinlet, Cd,inlet, routlet and Cd,outlet. Outlet orifice is open gradually due to the mechanics of the armature. This is taken in to account by multiplying the e↩ective area with the armature travel percentage. Figure 4.4: Abstraction of valve volumes, and flow paths. The following subsections will present the simulation algorithm in the order of execution for each loop. 4.4.1 Armature Motion The armature motion is computed with the forces computed in the previous loop with order: eqs. 4.5, 4.6, 4.7. After computing this loops position, velocity and acceleration; if they exceed the range of motion position is capped and velocity and acceleration is set to zero. 4.4.2 Electrical and Magnetic Circuit Simulation The electrical current for this loop is computed with eq. 4.15. The applied voltage is calculate based on the time in the simulation mentioned in eqs 4.17 and4.18. Rtotal is computed with the current armature position and used to calculate current flux with eq. 2.2. Fmm is computed with eq. 2.1. Inductance voltage VL and change in electrical current for next step ddit is computed with eqs. 4.11 and 4.12. 4.4.3 Control Volume Changes Volume of the air gap and the chamber changes due to armature translation. This changes the temperature and the pressure in these control volumes. These processes are assumed to be adiabatic compression/expansion because the volume changes happen under in the order of us. P (i) = P (i 1) V (i 1) ✓ V (i) (4.19) ◆ V (i 1) (1) T (i) = T (i 1) V (i) (4.20) ✓ ◆ 4.4.4 Gas Flows The order of gas flow computation is from downstream to upstream. First the mass flow from chamber to downstream reservoir ṁc,d and its e↩ects on the Mchamber, Pchamber and Tchamber are computed. Then the mass flow between chamber and air gap ṁc,a and its e↩ects on Mchamber, Pchamber Tchamber, Mairgap, Pairgap and Tairgap are computed. Finally the mass flow from upstream reservoir to chamber ṁu,c and its e↩ects on the Mchamber, Pchamber and Tchamber are computed. Computing Flow

Velocity M = Phigh (1) 2 (4.21) s Plow ✓ ◆ 1 Flow velocity between two pressure reservoirs is computed by the eq. 4.21 derived from the adiabatic flow equation [NASA, 2021]. If the resulting Mach number M is greater than 1, it is capped to 1 because the flow through orifices is choked. Computing Mass Flow Rate After computing flow velocity M one can compute the mass flow rate ṁ using the eq. 4.22 [NASA, 2021], where A is the orifice surface area, Pt is the total/upstream pressure, Tt is the total/upstream temperature, R is the gas constant and is the ratio of specific heats for the gas. +1 2(1) ṁ = pTt r R A Pt M 1 + 1 2 M2 (4.22) ✓ ◆ Computing Gas Charge/Discharge After computing the mass flow rate ṁ between two control volumes/reservoirs, the new mass M , pressure P and temperature T should be computed for the control volumes. m = ṁ dt = M (i) M (i 1) (4.23) M (i) = M (i 1) + m (4.24) To compute the next state of the control volumes it is assumed that the process is adiabatic. Thus we can write the following energy and mass conservation. m = M (i) M (i 1) e = M (i) u(i) M (i 1) u(i 1) = m h 0 = m h M (i) u(i) + M (i 1) u(i 1) 0 = m Cp T m M (i) Cv T (i) + M (i 1) Cv T (i 1) 0 = m T m M (i) T (i) + M (i 1) T (i 1) Eq. 4.27 leverages the fact that = CCpv to simply the expression. T (i) = m T m + M (i 1) T (i 1) M (i) T (i) 1 P (i) = P (i 1) ✓ T (i 1) Control volume states are computed with the equations above. ◆ (4.25) (4.26) (4.27) (4.28) (4.29) Computing Forces on Armature Last step of the simulation loop is to compute the forces acting on the armature. These forces are computed with the eqs. 2.1, 4.1, 4.2, 4.3 and 4.4. 4.5 Results Simulation is set with the following parameters: cr = 0.1mm ca = 0.1mm hC = 50mm rCout = 15mm Dw = 0.27mm tcf r = 1.5mm tcf a = 5mm tmba = 5mm tmta = 5mm rA = 4.9mm rcham = 2mm hcham = 2mm tshell = 2mm P R = 0.9 C S F = 0.75 hair = 1mm μ = 850 μ0 = 1.25663706212 · 10 6 H/m C W C C = 10 · 106 A/m2 erc = 1.68 · 10 8 ⌦ m tpowered on = 1.2 ⌧open tpowered of f = 1.2 ⌧close Figure 4.5: Electrical and magnetic circuit development over time. Figure 4.6: Forces acting on the armature. Figure 4.7: Motion on the armature. Figure 4.8: Change of the volume Figure 4.9: Mass flows to and from control volumes. Figure 4.10: Change of the mass Figure 4.11: Control volume pressure and temperature Figure 4.12: Pressures of control volumes and reservoirs. Chapter 5: Discussion Chapter 5 DISCUSSION 1 Chapter 2: Magneto Motive Force 2 Chapter 2: Magneto Motive Force 3 Chapter 2: Magneto Motive Force 4 Chapter 2: Magneto Motive Force 5 Chapter 2: Magneto Motive Force 6 Chapter 2: Magneto Motive Force 7 Chapter 2: Magneto Motive Force 8 Chapter 2: Magneto Motive Force 9 Chapter 2: Magneto Motive Force 10 Chapter 3: Magnetic Model of a Solenoid Valve 11 Chapter 3: Magnetic Model of a Solenoid Valve 12 Chapter 3: Magnetic Model of a Solenoid Valve 13 Chapter 3: Magnetic Model of a Solenoid Valve 14 Chapter 3: Magnetic Model of a Solenoid Valve 15 Chapter 4: Dynamic Model of a Solenoid Valve 16 Chapter 4: Dynamic Model of a Solenoid Valve 17 Chapter 4: Dynamic Model of a Solenoid Valve 18 Chapter 4: Dynamic Model of a Solenoid Valve 19 Chapter 4: Dynamic Model of a Solenoid Valve 20 Chapter 4: Dynamic Model of a Solenoid Valve 21 Chapter 4: Dynamic Model of a Solenoid Valve 22 Chapter 4: Dynamic Model of a Solenoid Valve 23 Chapter 4: Dynamic Model of a Solenoid Valve 24 Chapter 4: Dynamic Model of a Solenoid Valve 25 Chapter 4: Dynamic Model of a Solenoid Valve 26 Chapter 4: Dynamic Model of a Solenoid Valve 27 28