Proceedings of the ASME/BATH 2015 Symposium on Fluid Power and Motion Control
FPMC2015
October 12-14, 2015, Chicago, Illinois, USA

FPMC2015-9559

DYNAMICAL MODEL RESEARCH ON ENERGY-CONVERSION PROCESS OF GIANT MAGNETSTRICTIVE MATERIALS-BASED ELECTROHYDROSTATIC ACTUATOR

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ABSTRACT

A giant Magnetstrictive materials-based Electro-hydrostatic Actuator(MEHA) is shown by presenting its structure configuration and working principle, which include a Giant Material Actuator(GMA), pump, two one-way check valves, a cylinder and utilize fluid rectification via one-way check valves to amplify the small, high-frequency vibrations of GMA into large motions of a hydraulic cylinder.

The established dynamic model of a MEHA involves five submodels from the viewpoint of energy conversion: the dynamic model of the power amplifier; the dynamic magnetization model that describes the relationship between the exciting current and the magnetization of the Giant Magnetostrictive Material(GMM) rod; the magnetoelastic model describing the relationship between the magnetostrictive strain and the magnetization of GMM rod; the kinetic model of the GMA describing the relationship between the GMA displacement (piston displacement of pump) and the magnetostrictive strain; the cylinder motion model.

By the simulation to the above model, dynamic characteristics of MEHA are clearly exhibited by the dynamic response curves, which show a good agreement with the experimental data and gives a scientific explanation about the test results.

INTRODUCTION

Hydraulic systems have been widely used in industry for decades in applications where it is advantages to have the following features: the ability to manoeuvres' large loads, high force/torque-to-mass ratio, obtain accurate control of position, velocity and force. Due to these features hydraulic systems have also found wide applications in aerospace systems, where conventional hydraulic actuators typically rely on a central supply of high-pressure fluid along with a controllable servovalve to distribute this fluid to hydraulic output devices, but their need for hydraulic fluid lines can make them unsuitable for distributed actuation applications and Power-By-Wire(PBW) systems, which eliminated the necessity of mechanical linkages to actuate the flight surface control mechanism by replacing them with electrically controlled valves. The Electro-Hydrostatic Actuator (EHA) is one kind of PBW actuators and used to actuate the aircrafts' flight surfaces. By removing the central hydraulic power supply together with hydraulic pipes, an EHA's reliability and efficiency are greatly improved.

The high energy density of smart materials such as magnetostrictives makes them attractive for aerospace actuator applications where size and weight are critical design considerations, smart material EHAs can utilize fluid rectification via one-way check valves to amplify the small, high-frequency vibrations of certain smart materials into large motions of a hydraulic cylinder[1].

In this paper, a Giant magnetstrictive materials-based Electro-Hydrostatic Actuator(MEHA) is shown by presenting its structure configuration and working principle, which include a Giant Material Actuator(GMA), pump, two one-way check valves, a cylinder and utilize fluid rectification via one-way check valves to amplify the small, high-frequency vibrations of GMA into large motions of a hydraulic cylinder.

STRUCTURE CONFIGURATION

What Fig.1 shows is schematic diagram of MEHA. The MEHA consists of four separate parts: a pumping section, a hydraulic cylinder, an accumulator and the tubing & fittings. As the power provider of MEHA, the pump section is driven by an alternating magnetic field which comes from alternating current. The magnetic field intensity flux which is generated from current can form a closed magnetic flux through the GMM rod, bottom cap, pump body, top cap, output shaft. And GMM rod is eventually magnetized. The magnetized GMM rod can produce displacement and drive the piston movement back and forth constantly. The pump chamber can absorb or drain fluid due to the change of the volume. This can provide output power by using the principle of frequency rectification which is passive unidirectional reed valves housed inside the pump head.

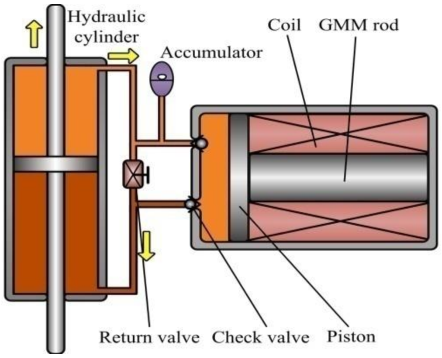


Fig.1 Section view of MEHA assembly

As Fig.1 shows, the operation of the MEHA can be divided into four stages: compression, exhaust, expansion, and intake[2,3,4].

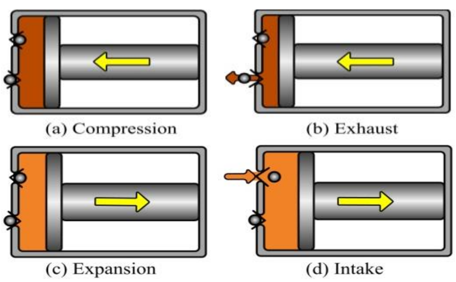


Fig.2 Operation principle of MEHA

(1)Compression:with sinusoidal electricity supply, expansion of GMM rod pushes hydraulic fluid in the closed pump chamber, resulting in the increase in pressure in the chamber.

(2) Exhaust: At the exhaustion stage, the outlet valve opens due to the pressure difference, then fluid starts to flow out of the chamber into the outlet tube, and the pressure builds up in the high-pressure-driven side of the output cylinder and results in motion of the output shaft.

(3) Expansion: The stage is similar to the compression stage, except that the stack starts to retreat with decreasing applied field, causing the pressure drop in pumping chamber.

(4) Intake: At the stage, the pressure in the pump chamber drops further to crack open the intake reed valve and allows fluid to flow from the low-pressure-driven side of the output cylinder back into the chamber.

These four stages are repeated every pump cycle and result in a net mass flow rate out of the pump through the outlet tube and an equivalent mass flow rate into the pump through the inlet tube.

MODEL

The energy-conversion process in a MEHA involves five stages: the stage from the input voltage to the applied current of the drive coil, the stage from the electrical energy to the magnetic energy, the stage from magnetic energy to the elastic potential energy, the stage from the elastic potential energy to the hydraulic energy and the stage from the hydraulic energy to the mechanical energy.

In the first two stages, electrical-magnetic energy transformation is achieved, and the middle or the third stage implements a magnetoelastic energy transformation, in the last two stages, the elastic-hydraulic energy and the hydraulic-mechanical energy transformation are obtained respectively.

Thus, the established dynamic model of a MEHA involves five submodels from the viewpoint of energy conversion: the dynamic model of the power amplifier; the dynamic magnetization model that describes the relationship between the exciting current and the magnetization of the Giant Magnetostrictive Material(GMM) rod; the magnetoelastic model describing the relationship between the magnetostrictive strain and the magnetization of GMM rod; the kinetic model of the GMA describing the relationship between the GMA displacement (piston displacement of pump) and the magnetostrictive strain; the cylinder motion model.

Dynamic Magnetization model of GMM rod

In a closed magnetic circuit, the applied magnetic field H generated by an alternating current is given by

$$H = \frac{Ni}{k_{\mathrm{f}} L_{\mathrm{G}}} = \frac{NI_{\mathrm{m}}}{k_{\mathrm{f}} L_{\mathrm{G}}} \cos \omega t = H_{\mathrm{m}} \cos \omega t \qquad (1)$$

where N is the number of the excitation coil turns, Im is the amplitude of the alternating current, k_{f} is the leakage coefficient of the magnetic flux, L_{G} is the length of GMM rod, Hm is the amplitude of applied magnetic field, ω is the angular frequency.

When GMM rod is excited by high frequency alternating current, the eddy loss in GMA appear, which will slow down the response speed of GMA. The magnetization intensity of the GMM rod in steady state M can be written as

$$M = (|\mu_{\mathrm{r}}| - 1) H \qquad (2)$$

Energy of magnetization for eddy loss in dynamic state can be written as[5][6]

$$\begin{aligned} \mu_0 \int M_{\mathrm{eddy}} \mathrm{d}H_{\mathrm{c}} &\approx \mu_0^2 \int \frac{D_{\mathrm{G}}^2}{2\rho\beta} \left(\frac{\mathrm{d}M}{\mathrm{d}t} \right)^2 \mathrm{d}t \\ &= \mu_0^2 \frac{D_{\mathrm{G}}^2}{2\rho\beta} \int \frac{\mathrm{d}M}{\mathrm{d}t} \frac{\mathrm{d}M}{\mathrm{d}H_{\mathrm{c}}} \frac{\mathrm{d}H}{\mathrm{d}t} \mathrm{d}t \end{aligned} \qquad (3)$$

Where M_{eddy} is the magnetization intensity for eddy losss, ρ and D_{G} are the electrical resistivity and the diameter of the GMM rod, respectively, β is a geometrical factor.

Get derivative to t both sides of the equation (3)lead to

$$M_{\mathrm{eddy}} \approx \mu_0 \frac{D_{\mathrm{G}}^2}{2\rho\beta} \frac{\mathrm{d}M}{\mathrm{d}t} \frac{\mathrm{d}M}{\mathrm{d}H} = \mu_0 (|\mu_{\mathrm{r}}| - 1) \frac{D_{\mathrm{G}}^2}{2\rho\beta} \frac{\mathrm{d}M}{\mathrm{d}t} \qquad (4)$$

Consequently the energy equation considering eddy loss based on equation (4) is

$$\int M\mathrm{d}H=\int(|\mu_{\mathrm{r}}|-1)H\,\mathrm{d}H-\int M_{\mathrm{eddy}}\mathrm{d}H \tag{5}$$

Get derivative to H_{c} both sides of the equation (5) lead to

$$\begin{aligned}M&=\mu_0|\mu_{\mathrm{r}}|H-M_{\mathrm{eddy}}\\&=(|\mu_{\mathrm{r}}|-1)H-\mu_0(|\mu_{\mathrm{r}}|-1)\frac{D_{\mathrm{G}}^2}{2\rho\beta}\frac{\mathrm{d}M}{\mathrm{d}t}\end{aligned} \tag{6}$$

Taking the Laplace transform of equation (6), so the actual magnetic induction intensity B in GMM rod is

$$M=\frac{(|\mu_{\mathrm{r}}|-1)H}{\mu_0(|\mu_{\mathrm{r}}|-1)\dfrac{D_{\mathrm{G}}^2}{2\rho\beta}s+1}=\frac{(|\mu_{\mathrm{r}}|-1)H}{\tau s+1} \tag{7}$$

Where $\tau=\mu_0(|\mu_{\mathrm{r}}|-1)\dfrac{D_{\mathrm{G}}^2}{2\rho\beta}$ is eddy current time constant.

Magnetoelastic model

When the MEHA is excited by the current acting on the driving coil, the process of magnetic-mechanic coupling can be expressed by Fig.3.

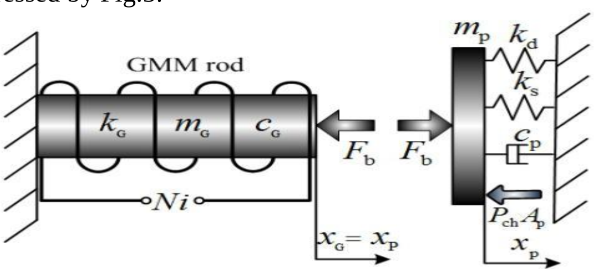


Fig.3 Sketch of GMA magnetic-mechanic coupling

As the discussion in Reference[7], the magnetostrictive λ is given by

$$\lambda=\frac{3}{2}\frac{\lambda_{\mathrm{S}}}{M_{\mathrm{S}}^2}M^2 \tag{8}$$

where λ_{S}, M_{S} are the saturation magnetostrictive and the saturation magnetization, respectively.

When the magnetic field intensity changed in a limited extent, the magnetostrictive force generated by GMM rod can be defined as:

$$F_{\mathrm{G}}=A_{\mathrm{G}}E_{\mathrm{G}}\lambda \tag{9}$$

Where A_{G} is cross-sectional area of GMM rod; E_{G} is the elasticity modulus of GMM rod, λ is magnetostrictive rate;

As Fig.3 shows, based on the principle of structure dynamics, the equation of motion of the piston is written by considering it as an single degree of freedom (SDOF) system as follows:

$$(m_{\mathrm{p}}+\frac{m_{\mathrm{G}}}{3})\ddot{x}_{\mathrm{p}}+(c_{\mathrm{p}}+c_{\mathrm{G}})\dot{x}_{\mathrm{p}}+(k_{\mathrm{d}}+k_{\mathrm{s}}+k_{\mathrm{G}})x_{\mathrm{p}}=F_{\mathrm{G}}-P_{\mathrm{ch}}A_{\mathrm{p}} \tag{10}$$

where m_{p}, m_{G} is the mass of piston and GMM rod, c_{p}, c_{G} is damping constant of piston and GMM rod, k_{d}, k_{s}, k_{G} is stiffness of metal diaphragm, spring and GMM rod, p_{ch} is pressure of pump chamber, A_{p} cross-sectional area of piston. F_{b} is the force acting on GMM rod that prevents it from reaching its free strain.

Fluid pressure model

In the fluid pumping chamber, the pressure (P_{ch}) is governed by the following pressure change rate (i.e. continuity) equation inside the chamber.

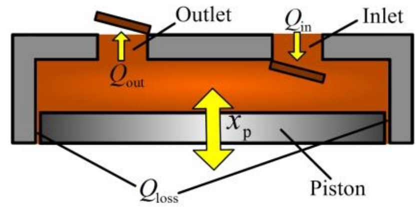


Fig.4 Schematic of fluid flow in pump chamber

As Fig.4 shows, the corresponding rate of pressure change inside the chamber can be obtained as below[8,9]

$$\dot{p}_{\mathrm{ch}}=\beta_{\mathrm{e}}\frac{A_{\mathrm{p}}\dot{x}_{\mathrm{p}}+Q_{\mathrm{in}}-Q_{\mathrm{out}}-Q_{\mathrm{loss}}}{A_{\mathrm{p}}(h-x_{\mathrm{p}})} \tag{11}$$

where Q_{in}, Q_{out}, Q_{loss}, h is inlet flow rate, outlet flow rate, loss of flow rate and the height of pump chamber.

Reed Valve model

Both the inlet and outlet reed valves can be considered as single degree-of-freedom mass-spring- damper system in the mechanical domain. As is shown in the Fig.5, using Newton's method of moment balance the equations of motion for the outlet and inlet rectification reed valves are:

$$\begin{cases}J_{\mathrm{Ri}}\ddot{\theta}_{\mathrm{Ri}}+c_{\mathrm{Ri}}\dot{\theta}_{\mathrm{Ri}}+k_{\mathrm{Ri}}\theta_{\mathrm{Ri}}=(p_{\mathrm{tL}}-p_{\mathrm{ch}})A_{\mathrm{Rb}}L_{\mathrm{Ri}} & p_{\mathrm{tL}}A_{\mathrm{Ra}}>p_{\mathrm{ch}}A_{\mathrm{Rb}}\\ \theta_{\mathrm{Ri}}=0 & p_{\mathrm{tL}}A_{\mathrm{Ra}}<p_{\mathrm{ch}}A_{\mathrm{Rb}}\end{cases} \tag{12}$$

$$\begin{cases}J_{\mathrm{Ro}}\ddot{\theta}_{\mathrm{Ro}}+c_{\mathrm{Ro}}\dot{\theta}_{\mathrm{Ro}}+k_{\mathrm{Ro}}\theta_{\mathrm{Ro}}=(p_{\mathrm{ch}}-p_{\mathrm{th}})A_{\mathrm{Rb}}L_{\mathrm{Ro}} & p_{\mathrm{th}}A_{\mathrm{Rb}}<p_{\mathrm{ch}}A_{\mathrm{Ra}}\\ \theta_{\mathrm{Ro}}=0 & p_{\mathrm{th}}A_{\mathrm{Rb}}>p_{\mathrm{ch}}A_{\mathrm{Ra}}\end{cases} \tag{13}$$

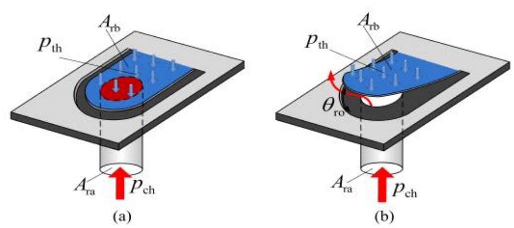


Fig.5 Schematic diagram of inlet and outlet reed valve

Where $J_{\mathrm{Ri}},J_{\mathrm{Ro}}$, $c_{\mathrm{Ri}},c_{\mathrm{Ro}}$, $k_{\mathrm{Ri}},k_{\mathrm{Ro}}$ are equivalent rotational inertia, damping, stiffness of inlet and outlet reed valve respectively, $\theta_{\mathrm{Ri}},\theta_{\mathrm{Ro}}$ is modeled as the angle of the inlet and outlet rectification reed valve, $A_{\mathrm{Ra}},A_{\mathrm{Rb}}$ is the action area on inlet and outlet reed valve by fluid, $L_{\mathrm{Ri}},L_{\mathrm{Ro}}$ is the length between the valve port and axis of oscillation.

Cylinder motion model

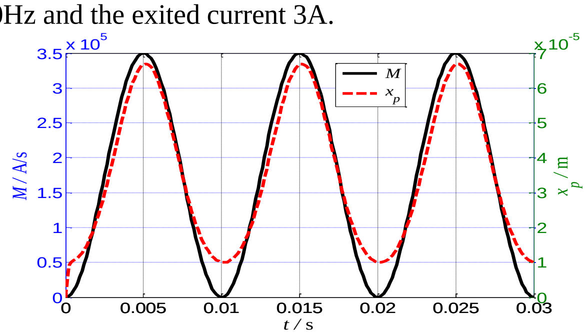
The mass of the piston and actuator load, typically attached to the free end of the piston, are lumped into a single mass, m_{L}, based on the assumption that the piston shaft is rigid. In the simplest case the actuator load is purely inertial, and a general mass-spring-damper system where the dissipation in the load is accounted for by damping term, c_L, and stiffness by, k_L. The motion equation for the general case can be expressed as

$$(p_h - p_L)A_L - F_L = m_L\ddot{x}_L + c_L\dot{x}_L + k_L x_L \qquad (14)$$

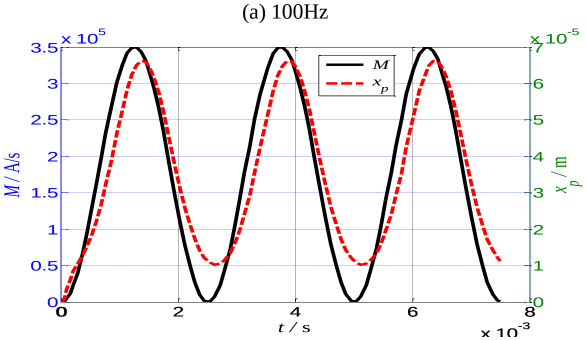
MODEL RESULTS AND DISCUSSION

The dynamic process in a MEHA by a sine-input current involves five stages: the stage from the input current to the excited magnetic field, the stage from the excited magnetic field to the magnetization of GMM rod, the stage from the magnetization to the elastic strain of GMM rod, the stage from the elastic strain of GMM rod to the fluid control pressure of MEHA and the stage from he fluid control pressure to the shaft motion of cylinder. In the first two stages, electrical-magnetic energy transformation is obtained, and the latter two stages achieves megnetic-hydraulic energy amplification.

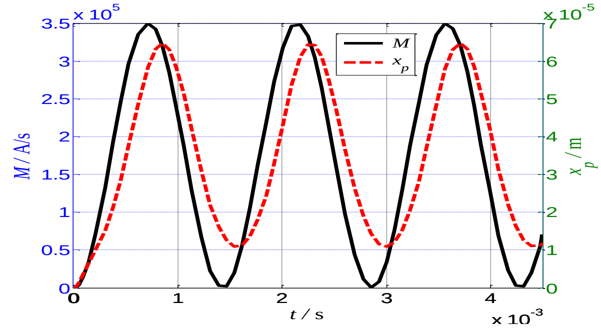
In the model part in this paper, the dynamic magnetization model of GMM rod, which described the eddy current effect acting on the GMM rod, is built; also, magnetoelastic model have been established, these two models depicted the dynamic energy conversion process of electromagnetic and magnetoelastic in the MEHA respectively, with the increasement of excited frequeny, a dynamic lag appears and varies with the excited frequeny, so, aim to distinguish the effect degree to dynamic lag by electromagnetic and magnetoelastic energy conversion process in the MEHA, a group of sine response curve are shown as figure 6 from the exited frequency 100Hz to 1000Hz and the exited current 3A.



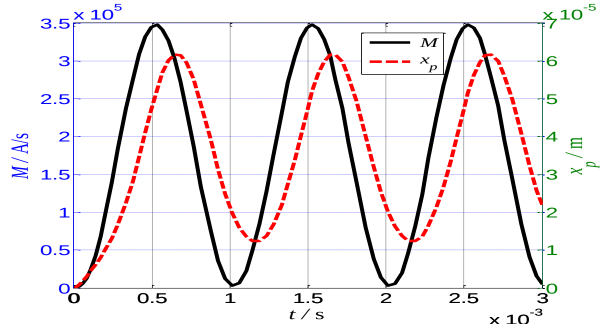
(a) 100Hz



(b) 400Hz



(c) 700Hz



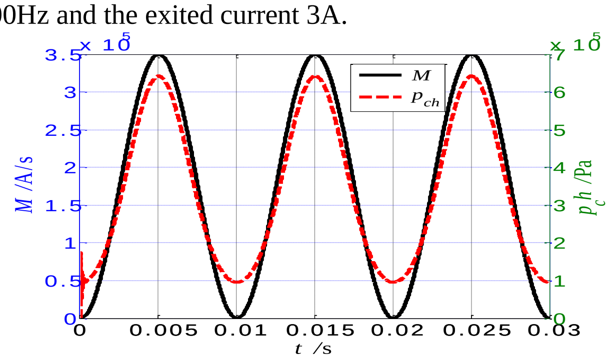
(d) 1000Hz

Fig.6 Magnetization and magnetostrictive free pisplacement at different frequencies

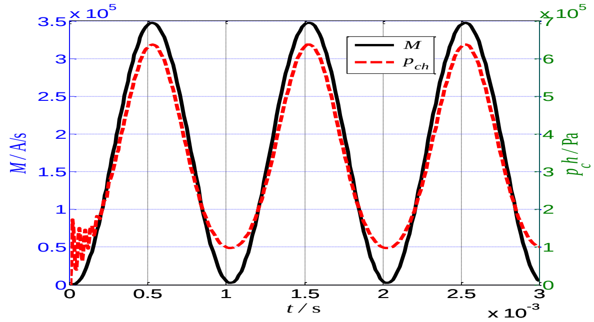
As Figure 6 shows, the left vertical coordinates expresses magnetization intensity, and the right vertical coordinates expresses the free pisplacement of piston driven by magnetostrictive rod.

Under 400Hz, the free pisplacement of piston keep a unremarkable lag behind with the magnetization intensity, with the increasement of the excited frequency, about over 400Hz, the free pisplacement of piston remarkablely delayed with the magnetization intensity. In addition, it can be found that the magnetization intensity curves almost unchanged when the excited frequency is less than 1000Hz, which illustrated that the magnetoelastic energy conversion process plays a decisive role in electromagnetic and magnetoelastic energy conversion in the MEHA.

Based on equation(11), it can be supposed that Q_{in}=0, Q_{out}=0, then, the blocked pressure curves in the champer of pump can be obtained with the exited frequency 100Hz, 1000Hz and the exited current 3A.



(a) 100Hz



(b) 1000Hz

Fig.7 Magnetization and blocked pressure in the champer of pump at different frequencies

As shown in the figure 7, in the above excited conditions, the blocked pressure exceed 0.6MPa, which show the load capacity supported by the MEHA, moreover, a interesting result have been exhibited in the figure 7, there are no phase lag between the magnetization intensity and the blocked pressure disappear even if the excited frequency reach to 1000Hz, which is just the essential property of the blocked pressure, because in this situation the GMM rod only make a minor movement.

Fig.8 shows the comparison between the output displacement simulation track of the MEHA hydraulic cylinder and the experiment data that measured by the laser displacement sensor. The simulation has good agreement with the measured data.

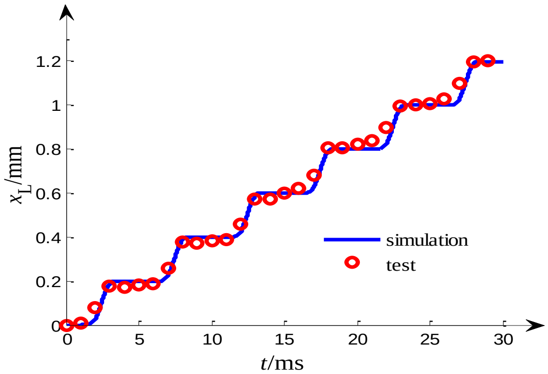


Fig.8 Output displacement of the cylinder at 200Hz

The relationship between the MEHA output flow rate and the driving frequency with no-load is shown in Fig.9.

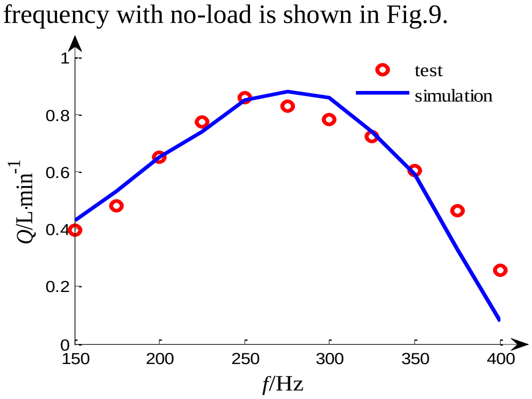


Fig.9 Output flow rate of the MEHA at different frequencies

Under 300Hz, the MEHA output flow rate rised with the increasement of the driving frequency, it reach to 0.8L/min when the driving frequency is approaching to 300Hz, the model rerults agree well with the measured data.

CONCLUSION

(1)The established dynamic model of a MEHA involves five submodels from the viewpoint of energy conversion: the dynamic model of the power amplifier; the dynamic magnetization model that describes the relationship between the exciting current and the magnetization of the Giant Magnetostrictive Material(GMM) rod; the magnetoelastic model describing the relationship between the magnetostrictive strain and the magnetization of GMM rod; the kinetic model of the GMA describing the relationship between the GMA displacement (piston displacement of pump) and the magnetostrictive strain; the cylinder motion model.

(2)The dynamic lag between the dynamic magnetization model and the magnetoelastic model of GMM rod are analyzed by the model results, the results shows, under 400Hz, the free piston placement keep a unremarkable lag behind with the magnetization intensity, but, about over 400Hz, the free pisplacement of piston remarkablely delayed with the magnetization intensity. moreover, the magnetoelastic energy conversion process plays a decisive role in electromagnetic and magnetoelastic energy conversion in the MEHA.

(3)The MEHA output flow rate with no-load, under 300Hz, rised with the increasement of the driving frequency, which can reach to 0.8L/min in the driving frequency around 300Hz, the model rerults agree well with the measured data.

NOMENCLATURE

H Applied magnetic field
N Number of the excitation coil turns
k_f Leakage coefficient of the magnetic flux
L_G Length of GMM rod
H_m Amplitude of applied magnetic field
ω Angular frequency of input current
ρ Electrical resistivity the GMM rod
D_G Diameter of the GMM rod
β Geometrical factor
μ_0 Air permeability
μ_r Relative permeability of GMM rod
M Magnetization intensity of the GMM rod in steady state
M_{eddy} The magnetization intensity for eddy losss
τ Eddy current time constant
λ Magnetostrictive rate
λ_S Saturation magnetostrictive
M_S Saturation magnetization
x_p Displacement of piston
m_p Mass of piston
m_G Mass of GMM rod
c_p Damping constant of piston
c_G Damping constant of GMM rod
k_d Stiffness of metal diaphragm

k_s Stiffness of spring
k_G Stiffness of GMM rod
p_{ch} Pressure of pump chamber
β_e Effective bulk modulus of hydraulic oil
A_G Cross-sectional area of GMM rod
E_G Elasticity modulus of GMM rod
F_G Magnetostrictive force generated by GMM rod
A_p Cross-sectional area of piston.
F_b Force acting on GMM rod
Q_{in} Inlet flow rate
Q_{out} Outlet flow rate
Q_{loss} Loss of flow rate
h The height of pump chamber.
J_{Ri}, J_{Ro} Equivalent rotational inertia of inlet and outlet reed valve
c_{Ri}, c_{Ro} Equivalent damping of inlet and outlet reed valve
θ_{Ri}, θ_{Ro} Angle of inlet and outlet rectification reed valve
A_{Ra}, A_{Rb} Action area on inlet and outlet reed valve by fluid.
L_{Ri}, L_{Ro} Length between the valve port and axis of oscillation.
p_{tL}, p_{th} Reed valve Pressure in low pressure side and high pressure side.
x_L Displacement of shaft of cylinder
m_L Mass of load and shaft of cylinder
c_L Equivalent damping of load and shaft of cylinder
k_L Equivalent stiffness of load and shaft of cylinder
p_h Pressure in high pressure side of cylinder
p_L Pressure in low pressure side of cylinder
F_L Load force

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China [grant number 51175243,]; the Natural Science Foundation of Jiangsu Province[BK20131359]; the Aeronautical Science Foundation of China [grant number 20130652011].

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