Demonstration Model of a Linear Permanent Magnet Actuator with Gas Springs

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Abstract- This paper describes the design and modeling of demonstration model of a linear permanent magnet actuator. This demonstration model used to verify the idea of using gas springs with linear permanent magnet actuator to produce strong vibrations for drilling applications.

I. INTRODUCTION

Linear permanent magnet machines with oscillatory motion have been widely proposed to operate as alternators and oscillatory motors often called as linear permanent magnet actuators. These devices would be advantageous in many applications like compressors, pumps, electromagnetic valve actuators, vibrators etc. In addition oscillatory motion of the linear actuator can be effectively utilized in more demanding drilling applications [1]. The power level required for drilling applications is higher than normal. With the conventional mechanical spring concept on both sides of the heavy mover will not produce sufficient fast oscillations. The mechanical springs are not well suited to oscillate heavy masses at higher frequencies due to mechanical constraints.

The concept of gas springs with linear machine can oscillate heavy mover mass at higher frequency to produce strong vibrations for drilling applications. The concept of integrating linear machine with gas springs is shown in Fig.1 this paper mainly describes the design and dynamic modelling of proposed demonstration model.

The entire machine on both sides is sealed with two end caps to create the gas spring effect on both sides of the piston. To keep the piston in centre position against the gravitational force, two simple mechanical springs are attached on both sides of mover as shown in Fig. 2b. By applying the proper current control depends on mover position, the piston will oscillate between the gas springs in resonance. In result of oscillating piston inside the machine the total casing also starts vibrating. These vibrations are effectively utilized in drilling applications. The piston and casing (stator) are moving in opposite directions.

The main dimensions of the demonstration model are:

1) length of machine: 80mm;
2) permanent magnet diameter: 15mm
III. ACTUATOR MODELLING

The dynamic behavior of the linear actuator is obtained from the standard set of electrical and force balance equations. The general electrical balance equation is given by

\[ V = I \cdot R + \frac{\partial \psi (x, i)}{\partial t} \]

\[ V = I \cdot R + \frac{\partial \psi}{\partial l} \cdot \frac{dl}{dt} + \frac{\partial \psi}{\partial x} \cdot \frac{dx}{dt} \]

where

- \( V \) voltage
- \( R \) winding resistance
- \( I \) current
- \( \psi \) coil flux linkage
- \( x \) relative displacement b/n piston and casing
- \( x_p \) piston displacement
- \( x_c \) casing displacement
- \( m_p \) piston mass
- \( m_c \) casing mass
- \( F_{em} \) electromagnetic force
- \( F_{gas} \) gas spring force
- \( F_f \) friction force
- \( F_g \) gravitational force

According to Newton’s theory the piston and casing are moving in opposite directions. So the force balance equation for the casing is same as piston with opposite polarity. Depend on the moving directions of piston and casing, the direction of gravitational force is changing. This demonstration model is used to verify the idea of integrating the linear machine with the gas springs to produce the strong vibrations for drilling applications. In view of this to simplify the dynamic analysis following assumptions are taken into considerations.

1. free oscillations of piston and casing are considered i.e. no load condition
2. the mechanical spring force considered very small compared to gas spring force
3. the piston is moving along the soft bearing material, considering no friction force. Due to difference in manufacturing tolerances some friction is existing but we didn’t consider in this case
4. the leakage of the gas from gas chamber is neglected.

A. Electromechanical force

The electromagnetic force depends on both relative position of piston and current. In order to obtain the force function, a grid displacement-current is used [2]. The program 2D-axi symmetric finite element analysis (FEM) is used to find the force for different values of current and position.
B. Gas spring force

Gas springs can store more energy than mechanical springs due to higher spring constant. The piston is compressing and decompressing the gas adiabatically, thus operating close to lossless operation. The air is used as gas spring in this model with initial pressure as same as atmospheric pressure. The equation for gas spring force with assumption of adiabatic compression and no losses is given by [3]

\[ F_{gg} = F_{g(T)} - F_{g(b)} = AP_0 \left[ \left( \frac{x}{x_g + x} \right)^{\gamma} - \left( \frac{x}{x_g - x} \right)^{\gamma} \right] \]

where
- \( F_{g(T)} \) force from top gas spring
- \( F_{g(b)} \) force from bottom gas spring
- \( A \) Area of gas chamber
- \( P_0 \) Initial gas spring pressure
- \( x \) piston moving distance from initial position
- \( x_g \) length of one gas chamber

![Fig.5. gas spring force vs. displacement](image)

C. Flux linkages

The total linkage flux is sum of the permanent magnet flux and the flux created by the coil current. The current-displacement grid was developed for both flux linkage and inductance

![Fig.6. Current-displacement grid for inductance](image)

![Fig.7. Current-displacement grid for flux linkage](image)

By using the bicubic spline approximation the parameters like \( \partial \Psi / \partial x \) and \( \partial \Psi / \partial i \) are determined. The dynamic simulations are done using MATLAB simulink model. Fig. (8-13) shows the results after simulations

![Fig.8. Piston displacement versus time](image)

![Fig.9. Casing displacement versus time](image)
It is clearly visible the gas springs are producing dominant force compared to the electrical force, as shown in Fig.13.

IV. CONCLUSIONS

This paper mainly describes the design and modeling of linear permanent actuator with gas springs. The actuator parameters like force, inductance and flux linkages are depend on both current and displacement. The current–displacement grids for those actuator parameters are developed using 2D-axisymmetric FEM. The gas springs force is highly dominated compared to electrical force generates high power equivalent to hydraulic hammers for drilling applications. The developed prototype results are not included. The main idea of integrating linear actuator with gas springs was verified successfully with the developed demonstration prototype.

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