A Novel Method to Minimize Force Ripple of Multimodular Linear Switched Reluctance Actuators/Motors

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Force ripple is the main disadvantage of conventional linear switched reluctance actuators/motors (LSRAs/LSRMs). Based on finite element analysis (FEA), a new method to minimize force ripple is proposed for multimodular LSRAs/LSRMs in this paper. First, the force distribution of an LSRA/LSRM module is computed by using FEA. Then, the scheme of the spatial distribution of modules is developed. Finally, the modular spatial displacement is optimized to minimize force ripple. The computed results based on the FEA demonstrate the proposed method. The proposed method does not require any change in both module design and motor control. Thus, it is simple, cost-low, feasible, and effective.

***Index Terms*—Force ripple, linear switched reluctance actuators/motors, minimization, optimization.**

I. Introduction

LINEAR switched reluctance actuators/motors (LSRAs/LSRMs) are an attractive candidate for applications to linear motion due to their following advantages: simple and robust construction, high fault tolerance, easy maintenance, less thermal problems and cooling arrangement, and low cost. Consequently, LSRAs/LSRMs have been investigated and developed for a number of applications, such as horizontal linear transportation systems, high-precision position systems in manufacturing automation, vertical transportation systems, elevator systems, and railway propulsion systems. Generally, high-power propulsion systems require LSRAs/LSRMs with multimodules. The multimodular LSRM presented in [1] is composed of three series-connected modules, which have the same double-sided four-phase magnetic structure. In [2], the proposed multimodular LSRM for a home elevator consists of two series-connected modules, which have the same double-sided four-phase magnetic structure and in which the translator has no yoke. In [3], the developed multimodular LSRM for a ship elevator includes 24 modules, which have the same double-sided four-phase magnetic structure. Hence, multimodular LSRAs/LSRMs consist of the specified number of series-connected modules and each module has the same magnetic structure. Furthermore, the spatial distribution of the propulsion force produced by each module is the same.

There is high force ripple in LSRAs/LSRMs [4]. Moreover, minimization of force ripple is crucial for motion performance of LSRAs/LSRMs. This paper is focused on this challenging issue. A novel, cost-low, feasible and effective method to reduce force ripple of multimodular LSRAs/LSRMs will be proposed. In the proposed method, a multimodular LSRA/LSRM consists of the specified number of modules. Each module or each group of modules produces the same magnitude of the propulsion force. However, the spatial vector of the force produced by each module or each group of modules may be different. The computed results based on finite element analysis (FEA) will demonstrate that the force ripple of multimodular LSRAs/LSRMs can be minimized through optimizing the spatial displacement between two adjacent modules or two adjacent groups of modules.

II. Proposed Method

A. Propulsion Force of Multimodular LSRAs/LSRMs

For a module, the coenergy of a phase is expressed as

$$W_m^{'}(y,i) = \int_0^i \psi(y,i)di \tag{1}$$

where ψ is the flux linkage, i is the current, and y is the displacement.

Hence, the propulsion force with the y direction is computed as

$$f_m(y,i) = \frac{dW_m'(y,i)}{dy} \tag{2}$$

It can be seen that the force is the nonlinear function of the displacement y and the current i. Assuming that a multimodular LSRA/LSRM consists of N_m modules, the computation of the propulsion force produced by a phase of the multimodular LSRM/LSRA is given as

$$\vec{F}_g = N_g \vec{F}_m \tag{3}$$

$$\vec{F}_{\mathrm{ph}} = \sum_{k=1}^{N_v} \vec{F}_{gk} \tag{4}$$

$$N_v = \frac{N_m}{N_g} \tag{5}$$

where $\vec{F}_m$ denotes the force vector produced by a module, $\vec{F}_g$ denotes the force vector produced by a group of modules, a group is composed of N_g modules that have the same spatial vector, N_v represents the number of groups.

If the first group is selected as the module reference, the magnitude of the force produced by the k-th group can be expressed as

$$F_{gk} = N_g f_m(y + \alpha_k, i) \tag{6}$$

where α_k denotes the spatial displacement of the k-th group with respect to the first group $(\alpha_1 = 0, k = 1, 2, \ldots, N_v)$.

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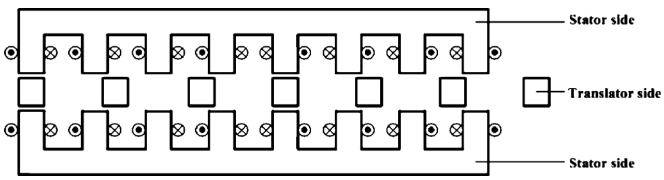


Fig. 1. Double-sided four-phase magnetic structure of a module.

Consequently, the phase force produced by the multimodular LSRAs/LSRMs is computed as

$$F_{\text{ph}}(y,i)=\sum_{k=1}^{N_v} N_g f_m(y+\alpha_k,i) \tag{7}$$

Thus, the propulsion force produced by the multimodular LSRMs/LSRAs is expressed as

$$F_{\text{SR}}(y,i)=\sum_{k=1}^{N_{\text{ph}}} F_{phk}(y,i) \tag{8}$$

where N_{ph} is the number of phases.

The force ripple factor is used to evaluate force ripple of LSRAs/LSRMs and is defined as

$$f_{\text{ripple}}=\frac{F_{\text{SR}\max}-F_{\text{SR}\min}}{F_{\text{SRave}}} \tag{9}$$

where $F_{\text{SR}\max}$ represents the maximum force, $F_{\text{SR}\min}$ represents the minimum force, and F_{SRave} represents the average force.

B. *Proposed Method*

For multimodular LSRAs/LSRMs, the force vector produced by each group has the same force distribution and may have the different spatial displacement. Consequently, the maximum force, the minimum force, the average force, and hence the force ripple factor are the function the spatial displacement between two groups, respectively. The proposed method can be summarized as the following: 1) the spatial distribution scheme of modules is developed in order to obtain the most symmetrical force characteristics; 2) the spatial displacement between any two adjacent modular groups is selected to be the same; and 3) the spatial displacement is optimized in order to minimize the force ripple factor of multimodular LSRAs/LSRMs.

In this paper, the objective function of the optimization is proposed as

$$f_{\text{ripple}}(\alpha^{\text{opt}})=\min\left\{\frac{F_{\text{SR}\max}(\alpha)-F_{\text{SR}\min}(\alpha)}{F_{\text{SRave}}(\alpha)}\right\} \tag{10}$$

where α represents the spatial displacement between any two adjacent groups.

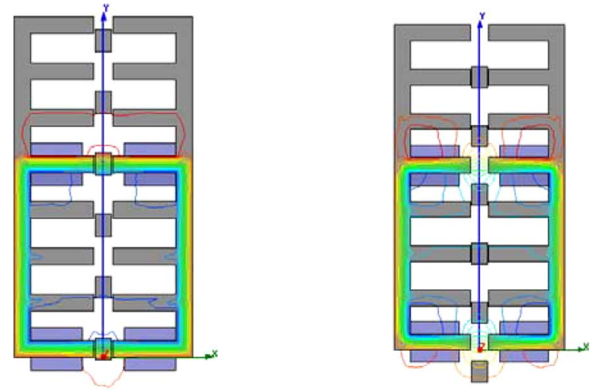
III. Minimization of Force Ripple in Multimodular LSRAs/LSRAMs

A. *Module of Multimodular Four-Phase LSRAs/LSRMs*

Fig. 1 illustrates the four-phase magnetic structure of the designed module for multimodular LSRAs/LSRMs. The physical dimensions of the module are described in Table I.

TABLE I
Physical Dimensions of the Designed Module

Parameters	Value	Parameter	Value
Stator pole width	13 mm	Translator pole width	17 mm
Stator slot width	23 mm	Translator slot width	31 mm
Stator pole height	49 mm	Translator pole height	13 mm
Stator yoke thickness	13 mm	Translator yoke thickness	0 mm
Stack length	43 mm	Air gap length	0.8 mm



(a) (b)

Fig. 2. Flux distributions computed by FEA for a module. (a) Completely aligned position. (b) Fully unaligned position.

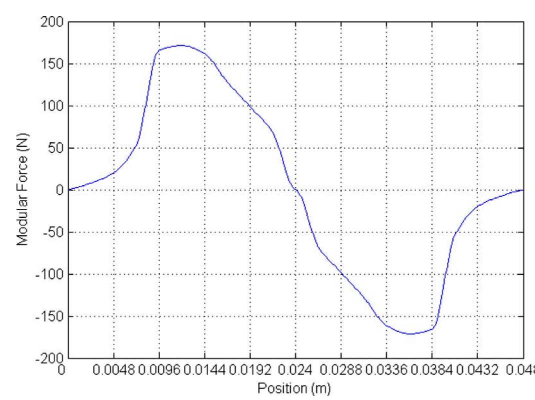


Fig. 3. Phase force characteristics computed by FEA for a module.

The propulsion force produced by a phase in the module is computed by the FEA. In this paper, the translator position is equal to 0 m if the translator pole is fully unaligned with the stator pole and the translator position is equal to the half translator pitch if the translator pole is completely aligned with the stator pole. The flux distributions at the aligned and unaligned positions computed by the FEA are illustrated in Fig. 2. The computed phase force characteristics produced by a module are depicted in Fig. 3.

B. *Spatial Distribution Schemes of Modules*

The proposed spatial distribution scheme of two modules is illustrated in Fig. 4 and the proposed spatial vector diagram is shown in Fig. 5, if the LSRA/LSRM consists of two modules.

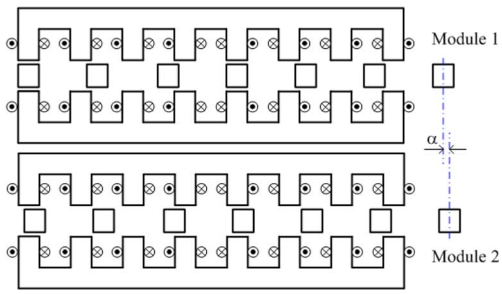


Fig. 4. Proposed spatial distribution scheme of two modules.

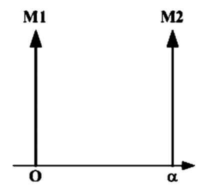


Fig. 5. Vector diagram of the proposed spatial distribution scheme of two modules.

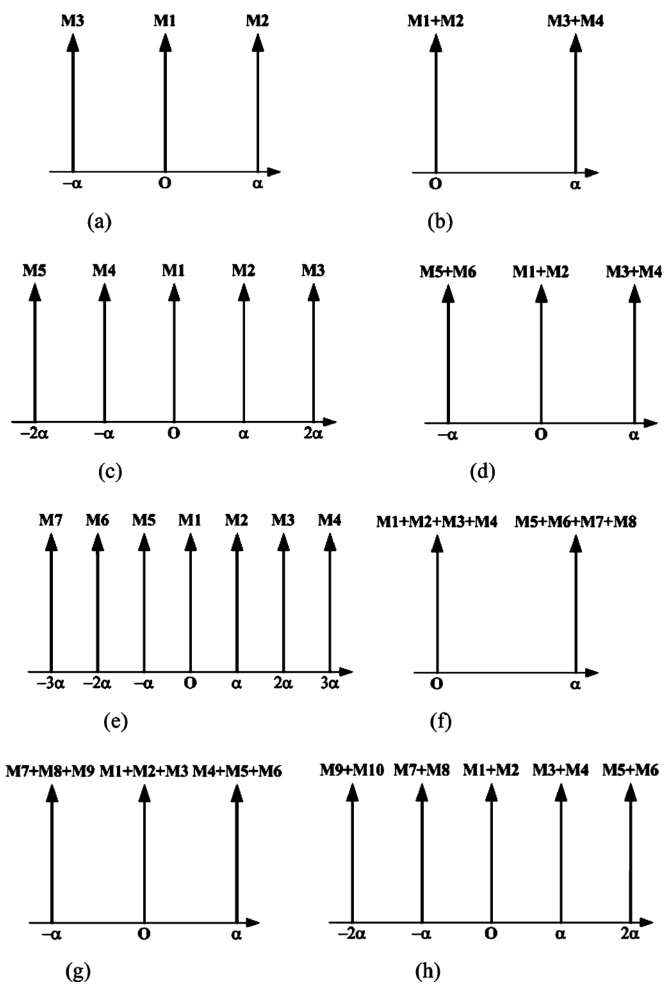


Fig. 6. Vector diagrams of the proposed spatial distribution schemes of various modules. (a) Three modules. (b) Four modules. (c) Five modules. (d) Six modules. (e) Seven modules. (f) Eight modules. (g) Nine modules. (h) Ten modules.

The proposed spatial distribution schemes of multimodules are depicted in Fig. 6.

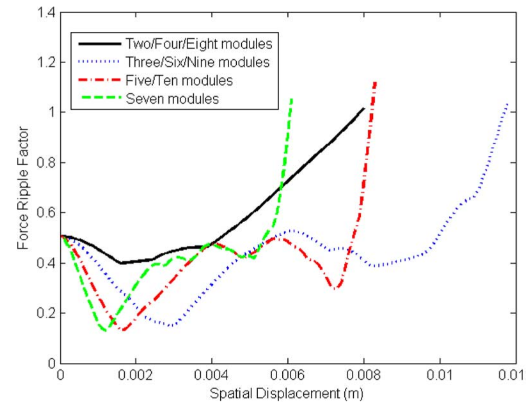


Fig. 7. Minimization of force ripple factor of the multimodular four-phase LSRA/LSRM.

TABLE II
COMPARISON BETWEEN PROPOSED AND CONVENTIONAL METHODS

Number of modules	Force ripple factor (Conventional)	Minimum force ripple factor (Proposed)	Reduction in force ripple factor
2	0.5057	0.3970	21.49%
3	0.5057	0.1475	70.83%
4	0.5057	0.3970	21.49%
5	0.5057	0.1295	74.39%
6	0.5057	0.1475	70.83%
7	0.5057	0.1291	74.47%
8	0.5057	0.3970	21.49%
9	0.5057	0.1475	70.83%
10	0.5057	0.1295	74.39%

C. *Minimization of Force Ripple Factor in Multimodular LSRAs/LSRMs*

Based on the schemes proposed in the last section, the optimized results are shown in Fig. 7.

It can be observed that the optimal spatial displacement for the arbitrary number of modules can be found by using the proposed method, to fulfill the minimum force ripple in the four-phase LSRA/LSRM. For the four-phase LSRA/LSRM with two, four and eight modules, three, six and nine modules, and five and ten modules, furthermore, the optimized results are the same, respectively. Figs. 5–6 show that their spatial distribution schemes of modules are similar, respectively. Thus, the aforementioned results are obvious.

IV. COMPARISONS

With various numbers of modules, the comparisons of the force ripple factor are described in Table II. It can be seen that the proposed method can reduce the force ripple factor notably in comparison with the conventional method. To be specific, the force ripple factor can be reduced by 21.49% at least and by 74.47% at most, due to the proposed method. Furthermore, the number of the modules has the considerable effect on improvement in the force ripple. Therefore, the computed results based on FEA have testified that the proposed method is feasible and effective.

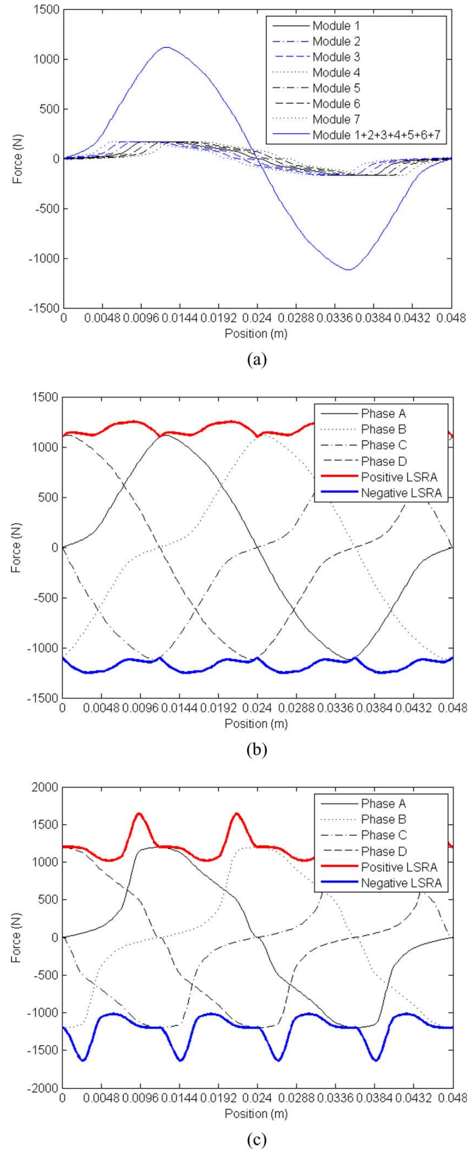


Fig. 8. Minimization of force ripple of the four-phase LSRA/LSRM consisting of seven modules. (a) Modular force waveforms with the optimal spatial displacement. (b) Force ripple with the proposed method. (c) Force ripple with conventional method.

It can be observed from Table II that the force ripple factor with the modular number of 2, 4, or 8 is larger than the one with the modular number of 3, 5, 6, 7, 9, or 10. The latter is reduced by more 70%. Therefore, the preferred numbers of modules are 7, 5, 10, 3, 6, and 9.

Fig. 8 illustrates the proposed modular force distribution, the resultant force of seven modules, and the force ripple waveforms from the proposed and conventional methods for the four-phase LSRA/LSRM with seven modules. It can be observed that the force ripple from the proposed method is much less than the one from the conventional method. It also demonstrates the proposed method.

It is desired that the positive force characteristics are fully symmetrical about the negative force characteristics for implementing good control performance. The proposed method aims at obtaining the best symmetrical force characteristics. The force characteristics of four-phase LSRAs/LSRMs are little nonsymmetrical if the number of modules is equal to 2, 4, or 8. However, the force characteristics of four-phase LSRAs/LSRMs are fully symmetrical if the number of modules is selected as 3, 5, 6, 7, 9 or 10.

V. Conclusion

This paper presents the novel method to reduce the force ripple in multimodular LSRAs/LSRMs. The computed results based on FEA have demonstrated that the force ripple in multimodular LSRAs/LSRMs can be improved notably due to the developed spatial distribution schemes of modules and the computed optimal spatial displacement, without any change in motor design or motor control. Therefore, the proposed method is cost-low, simple, feasible, and effective.

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