Overview of 2-Degree-of-Freedom Rotary-Linear Motors Focusing on Coupling Effect

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2-degree-of-freedom (2DoF) rotary-linear (RL) motors are capable of implementing pure rotary motion, pure linear motion or helical motion along the same axis, which have definite advantages of integrated structures, high material utilization, fast response and so on. Therefore, such motors have an extensive application prosperity ranging from robots, electric vessels, electric and hybrid vehicles, screwing machines, drilling machines, and intelligent machining systems, etc. In this paper, an overview of 2DoF RL motors is presented, which can be divided into the motors with crossed RL magnetic field and those with independent RL magnetic fields. The development of various topologies and the corresponding coupling effect, optimization designs and decoupling control algorithms are discussed and reviewed.

Index Terms**—2-degree-of-freedom rotary-linear motor, coupling effect, topology, optimization scheme, control algorithm, overview.**

I. INTRODUCTION

The traditional electrical machine can only produce rotary or linear motion separately, which can be divided into two types: rotary motor and linear motor. Therefore, for the applications needing both rotary and linear motions, the rotary-linear (RL) systems are always achieved by stacking at least one rotary motor on top of another, mounted with rotary-to-linear transmission mechanisms, as shown in Fig.1 [1] or more than 1 rotary motor and 1 linear motor with complex intermediate transmission mechanism. Obviously, they have the defects of complicated mechanics, enormous space requirements, frequent mechanical adjustments, high maintenance costs, and low reliability [2]. As a result, it is hard for them to satisfy the requirements of today's industrial market.

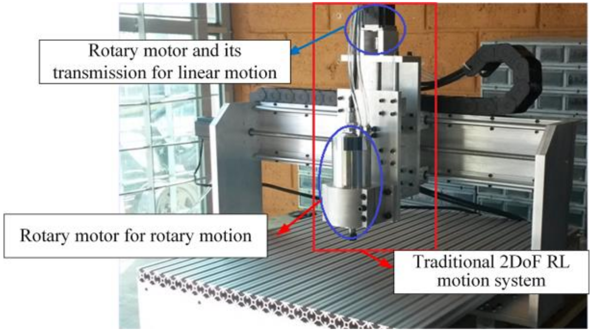


Fig.1.Traditional RL motion system.

Hence, the 2-degree-of-freedom (2DoF) RL motor, which can realize rotary motion, linear motion or 3-dimentional helical motion by employing only one motor, was proposed and attracted much attention from scholars. Compared with the traditional RL motion system, a 2DoF RL motor is much more integrated and room-saving due to the absence of intermediate mechanical devices. Therefore, the use of 2DoF drives may potentially provide benefits in terms of system simplicity, compactness and lightweight by permitting to integrate more functions into a single motor [3]. Thus the material utilization and response speed of the whole system will be improved. Therefore, replacing traditional RL motion system by the 2DoF RL motor has significant advantages in the intellectual industries such as pick-and-place robots [4], vacuum contactors [5], electric vehicles and hybrid electric vehicles [3, 6], screwing and drilling machine [7] and so on, as shown in Fig.2.

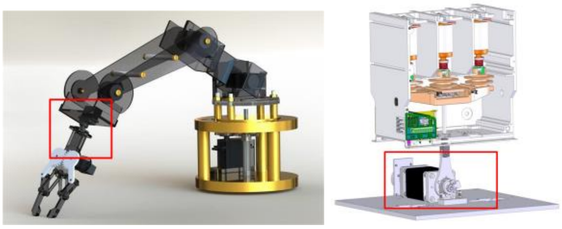

(a) (b)

Fig.2. Examples of potential applications of 2DoF RL motors. (a)Robotic arm. (b) Vacuum contactor.

As a novel type of the electric motor, the 2DoF RL motor breaks the understanding of the traditional 1DoF motor, greatly expands the research scope of the motor discipline, and brings a new driving concept, which greatly improves the overall performance of the motion control system. In addition, the research of the 2DoF RL motor involves some new problems. The biggest difference between traditional 1DoF motor and 2DoF motor is the magnetic field. The former only has one magnetic field, namely rotary or linear magnetic field, while the later has both rotary and linear magnetic fields. Therefore, one key problem of the traditional RL system, which is composed of multiple motors and mechanical devices, is to analyze and reduce the influence of mechanical coupling. However, for an integrated 2DoF motor with same function but without mechanical coupling, the research of electromagnetic coupling should be focused (e.g. [8-10]). In addition, due to the integrated topology and electromagnetic coupling, the design and optimization processes cannot utilize the traditional principles and methods directly. Moreover, the effective decoupled control strategies of 2DoF RL motors are necessary to achieve a high-precision position tracking for both the two axes simultaneously [11]. Apart from these, due to the unconventional layout of the magnetic core and/or windings, it is rather expensive and difficult to realize the specific manufacturing processes of 2DoF RL motors by using the classical manufacture method [3]. Therefore, it is vital to explore the nature of the electromagnetic coupling effect for 2DoF RL motors and quantify the performance influence produced by it. Moreover, optimizing the decoupled structures, achieving the decoupled control, and expanding 2DoF RL motors to commercial applications are also important.

This paper firstly gives an overview of the concept and development of the 2DoF RL motors. Then the topologies and the corresponding coupling effect existing in it as well as the related analyzing methods are discussed and summarized. After that, the optimization design methods are reviewed. Finally, the control algorithms, especially the decoupled control of 2DoF RL motors are presented and discussed.

II. CONCEPT AND DEVELOPMENT OF 2DOF RL MOTORS

The first structure of 2DoF RL motor was proposed by E. A. Mendrela from Poland in 1976 [12], named RL induction motor with solid rotor, as shown in Fig.3. It can be seemed simply as a conventional rotary and linear-tubular motor with the rotors joined stiffly. Tremendous researches were carried out by him [13-18], leading the development of this area. After that, a helical motion induction motor consisting of two tandem-connected sections having helical primary windings was proposed by J. J. Cathey from USA in 1988 [19, 20]. Japanese scholars Nobuyuki Iwatsuki and W.J. Jeon also carried out in-depth researches on 2DoF RL induction motors, which was composed of four stators and a common mover [21-23]. During this period, the researches of 2DoF RL motors mainly focused on induction motors. This type of motor is cheap, simple and easy to manufacture, which can be used in hostile environment. However, due to its inherent disadvantages such as low power density, the 2DoF RL induction motor develops slowly and needs to be further studied.

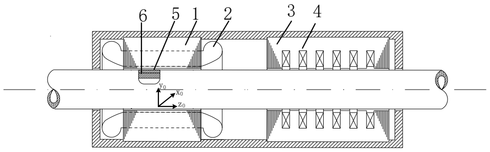


Fig.3. The first 2DoF RL induction motor [12].
1-armature producing rotating field, 2-winding of armature 1, 3-armature producing travelling field, 4-winding of armature 3, 5-rotor conducting sheet, 6-rotor iron core

With the development of permanent magnet (PM) motors, 2DoF RL PM motors have attracted considerable attentions. Seok-Myeong Jang from Korea proposed a 2DoF RL PM motor with cylindrical Halbach array in 2003 [24], as shown in Fig.4, which consisted of an exterior polar Halbach quadrupole array for a rotary motion and an interior cylindrical Halbach dipole array for a linear one. Then one RL PM motor with two independently energized three phase windings (Germany) [25] and a RL PM actuator with concentrated coils (France) [26], etc., have been put forward in the next few years. Compared with 2DoF RL induction motors, the 2DoF RL PM motors have the advantages of higher efficiency and output power but with higher cost and more complex structures, due to the magnet material utilization.

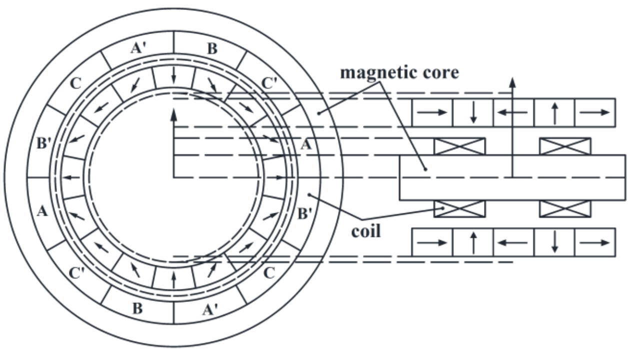


Fig.4. The 2DoF RL PM motor [24].

In 2007, Yasukazu Sato from Japan proposed one RL switched reluctance (SR) motor [27], as shown in Fig.5, which enriched the categories of 2DoF RL motors. It has a pair of the 6/4 SR motor stators coaxially coupled each other so that the salient poles of the relevant excitation phase were aligned. The torque and trust can be produced by unequal excitation of two stators. Apart from that, other topologies based on the SR principle such as multi-segmental RL SR motor (Romania) [28-30] were also proposed. Such motors have a high utilization factor of motor and rapid dynamic response speed, but high torque ripples are encountered, which should be avoided in its applications.

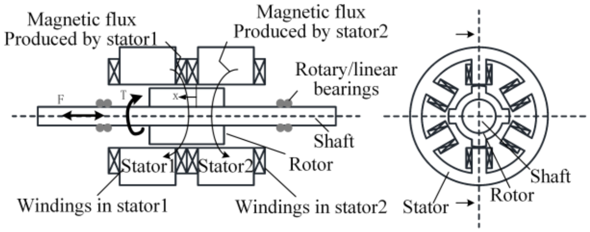


Fig.5. The 2DoF RL SR motor [27].

In addition, some 2DoF RL mixing-type motor topologies were proposed [31, 32], in which the rotation part and linear part were utilized different conventional machine topology, respectively. Hence, the 2DoF RL mixing-type motor inherits the advantages of both machines. On the other hand, some novel topologies such as RL isotropic brushless motors [3, 10, 33, 34], and micro RL ultrasonic motor for endovascular diagnosis and surgery [35] etc., have also been researched.

Conceptually, the 2DoF RL motor is a type of integrated machine producing pure rotary motion, pure linear motion or helical motion by a single motor. The main categories of 2DoF RL motors based on the operating principles are listed in Fig.6.

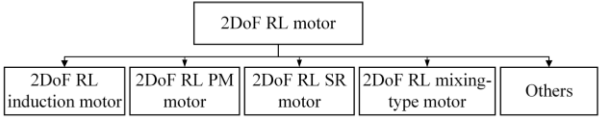


Fig.6. The main categories of 2DoF RL motors.

III. TOPOLOGIES AND COUPLING EFFECT OF 2DOF RL MOTORS

Compared with traditional RL motion systems, high integration is the most prominent advantage of 2DoF RL motors, which can be generally divided into two modules, namely the rotary and linear modules. However, there is inevitable electromagnetic coupling and mechanical coupling between the two modules. Therefore, it is essential to have a full cognition of coupling effect existing in various topologies of 2DoF RL motors. Based on the fact whether the rotary and linear magnetic fields are crossed or not, the topologies are divided into two categories, namely the motors with crossed RL magnetic field and the motors with independent RL magnetic fields. Besides, the corresponding coupling effect will be reviewed and discussed in this section.

A. 2DoF RL motors with crossed RL magnetic field

As shown in Fig.7, a classical 2DoF motor with crossed RL magnetic field was proposed in [36]. The stator consists of two sets of helical windings, which are placed on inner and outer bobbins. The mover is comprised of a shaft and PMs magnetized in the radial direction. Since the armature windings are helical structure, the rotary and linear magnetic fields will be generated synchronously by injecting 3-phases armature currents. Then the force and torque are produced respectively. It should be emphasized that the rotary magnetic field is crossed with the linear magnetic field, resulting in the coupling effect, which is analyzed by the finite element method (FEM). The results show that there is force in the rotary motion and a torque in the linear motion. In order to reduce the coupling effect between the two modules, the numbers of turns for the inner and outer windings are set as 21 and 32 respectively. This structure makes full use of the magnetic core and has a high output torque and force. However, the winding process of it is much complicated and the mover needs to be fully coated with PMs, which has a relatively high cost.

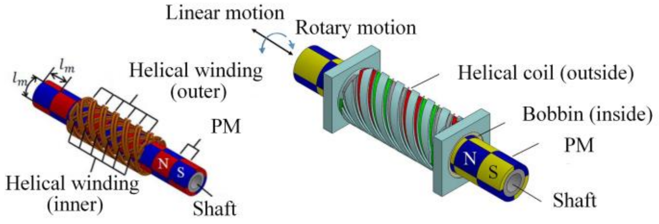


Fig.7. A cross-coupled 2DoF motor [36].

Fig.8 shows a 2DoF electromagnetic actuator with single stator [37]. The mover has 8 and 7 salient poles in the rotation direction and linear direction, respectively. In addition, both two stator cores have 6 salient poles in the two directions. Therefore, the way of rotation of 2DoF is the same as that of an 8 poles 6 slots PM synchronous motor, and the way of linear motion of 2DoF is the same as that of a 7 poles 6 slots PM linear synchronous motor. Apart from the mechanical coupling, there is electromagnetic coupling deduced by the end effect and crossed RL magnetic field. Based on the 3D FEM, the disturbing torque and force produced by the coupling effect are calculated. It is found that the back-EMF of the rotary coil in linear motion is less than 4% of that in rotary motion and the back-EMF of the linear coil in rotary motion is less than 5% of that in linear motion. Moreover, since the doubly salient topology is utilized, the high torque ripple is also a disadvantage needed to overcome.

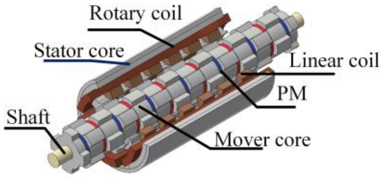


Fig.8. Basic structure of a 2DoF electromagnetic actuator[37].

Another 2DoF RL motor with crossed RL magnetic field was proposed in [8], as shown in Fig.9. It is composed of two arc-shaped stators of the rotary and linear parts respectively and a solid rotor coated with a copper layer. The two arc-shaped stators are assembled orthogonally into a whole stator, so the motor belongs to a single-stator one. The special image method and the 3D FEM are adopted to address the coupling effect produced by the end effect [38] and the mathematical model is established considering both the electromagnetic and mechanical coupling effect [39]. It is concluded that the coupling effect is related to the source frequency and leads to the decrease in the output torque and force. The modeling method of the coupling effect used here can be referenced to other 2DoF RL motors. Moreover, the proposed 2DoF split-stator induction motor with a solid mover is easy to manufacture with low cost, but the efficiency should be improved further for the industrial application.

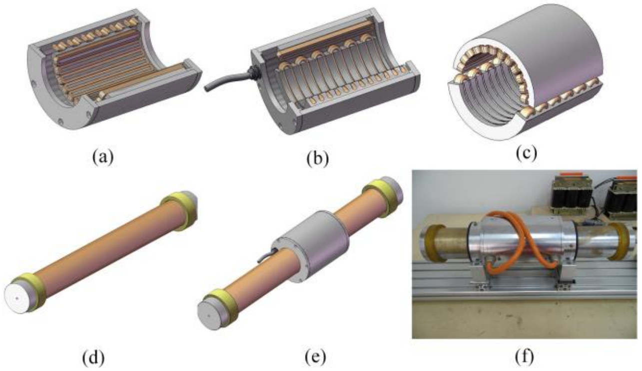


Fig.9. A 2DoF split-stator induction motor [8].
(a) Rotary motion arc-shaped stator, (b) Linear motion arc-shaped stator,
(c) Integrated stator, (d) Rotor, (e) Assembly, (f) Prototype.

In addition, there is also crossed RL magnetic field existing in a double-stator RL PM motor [40-42], as shown in Fig.10. It is composed of an outer stator and an inner stator with a hollow tubular mover containing toroidal- and arcuate-shaped PMs, which are alternately attached on the outer and inner surfaces of the mover, respectively. The outer stator and outer PMs constitute the linear module and the rotary module is comprised of the inner stator and inner PMs. The coupling effect is generated at the ending parts and double layer air-gap. In the linear module, the end effects between the PMs and the outer stator iron core leads to an increase of the detent force. In the rotary module, the end effects are different at the different mover position in Z direction, which is influenced by linear module. Besides the coupling effect caused by end effect mentioned above, the coupling degree of the two modules is also dependent on the magnetization characteristics of the mover core in the orthogonal crossed magnetic field produced by the orthogonally array of the two types of the PMs [43]. The testing model to analyze such magnetization characteristics of the mover consisting of excitation coils, reaction coils and PMs was built based on 3D FEM. It is concluded that the coupling effect degree varies with the excitation currents in the orthogonal crossed magnetic field. By setting suitable values for the orthogonal fluxes, the coupling effect degree can be reduced.

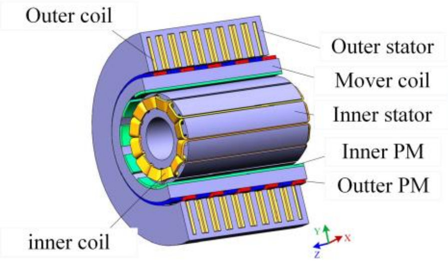


Fig.10. Double-stator RL PM motor [40-42].

Except for 2DoF RL induction and PM dual-stator motors, J. F. Pan proposed an integrated double-stator SR motor [1, 11], as shown in Fig.11. It consists of a rotor and two identical stator rings with windings with no phase shift. Both the two stators are not only the parts of the rotary module but also the components of the linear module. Thus, the rotary and linear magnetic fields are crossed and dependent. It should be emphasized that the rotor structure is the same as that of a conventional SR motor, which is shorter than the sum of the two stators. The force is attributed to the variation of magnetic reluctance principle. To analyze the coupling effect deduced by crossed RL magnetic field in this motor, the author formulated the expressions of the torque/force as functions of the stator currents. It is clear that torque and force generation are both dependent on the phase currents of the stators. Therefore, the magnetic paths are nonlinear and highly coupled, which is verified by FEM. It should be noted that the net torque profile from the three phases changes with large fluctuations at different mechanical angles and so does the force.

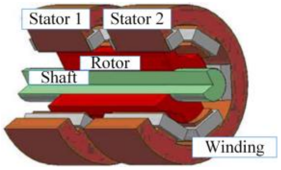


Fig.11. Integrated RL SR motor [1, 11].

Similarly, another category of 2DoF RL SR motor is shown in Fig.12, which can be considered as an efficient combination of a usual rotational SR machine and a special linear SRM having several mover modules on its shaft [30]. Except for the mechanical coupling effect caused by sharing the common rotor, the rotary module will produce coupling effect on linear motion. It is because that the linear motion, which is performed the correct feeding sequence, also depends on the angular position of the mover, meaning that there is crossed and dependent RL magnetic field in the air-gap. It is found that the mover also has a linear displacement at the speed of 0.5 m/s during the rotation due to the coupling effect [28]. Such motors have a relatively simple topology, which are easy to manufacture. However, due to the magnetic field coupling effect, the control strategies of 2DoF RL SR motors are more complex than the conventional SR motors. Moreover, the torque and force ripples are relatively high, which inherits the drawbacks of a SR motor.

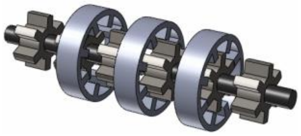
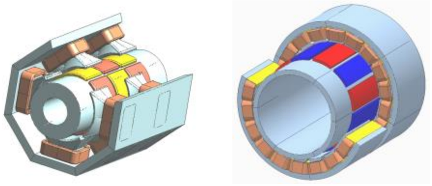


Fig.12. A multi-stator RL SR motor [30].

In [10, 33, 34, 44], a novel RL isotropic brushless machine and its variant topology were proposed, as shown in Fig.13. There is crossed RL magnetic field in both the structure shown in Fig.13 (a) with single stator and the structure shown in Fig.13 (b) featuring a modular layout composed of two identical stator modules. The author presented a decoupled control scheme to realize the decoupling of the rotary and linear modules. This kind of motor is more suitable for the power drives of short stroke on account of the limitation of its structure. In addition, based on the topology of RL isotropic brushless machine, a novel RL Halbach PM actuator (Fig.14) was proposed [45, 46], in which the rotary and linear magnetic fields are influenced by the coupling effect highly in the airgap.



(a) (b)

Fig.13. RL isotropic brushless machine and its variant structure [10]. (a) Cut-out view of brushless machine. (b) Cut-out view of basic variant of (a).

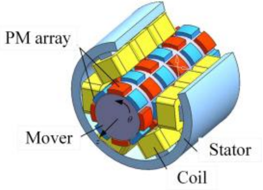


Fig.14. A novel RL Halbach PM actuator [45, 46].

B. *2DoF RL motors with independent RL magnetic fields*

In general, the 2DoF RL motors with independent RL magnetic fields can be simply considered as a combination of a rotary motor and a linear motor with a common mover. In such motors, the rotary and linear magnetic fields are produced by the corresponding rotary and linear stators respectively. However, there is also coupling effect between the two modules, which is mainly caused by the end effect and two-motion interact.

For the two-armature RL induction motor shown in Fig.3 and Fig.15 [18], which consists of a conventional rotary motor and a linear-tubular motor with the rotors joined stiffly, both electromagnetic coupling and mechanical coupling exist in it. The former is mainly caused by two factors: the magnetic fields coupling in the air-gap between the rotary and linear armatures reaction fields and the dynamic end effects produced by the linear motion on the rotary module. The mechanical coupling is caused on account of sharing the same rotor, which cannot be ignored. In order to weaken the magnetic fields coupling mentioned above, the distance between the rotary and linear armatures is extended. Moreover, the approach to addressing the coupling effect caused by dynamic end effects used in [47] is investigated based on the combination of the transient time-domain finite element model and frequency domain slip frequency technique. It is worth noting that the impact of this coupling effect is not significant at low axial speed of the rotor. The proposed method was verified by experimental results.

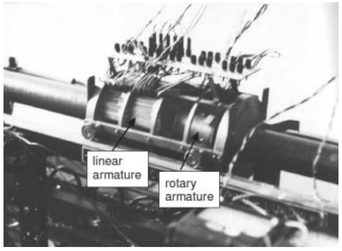


Fig.15. Laboratory model of twin-armature RL induction motor [18].

Similarly, Andrew Turner proposed one direct-drive RL PM actuation system for control of gearshifts in automated transmissions, as shown in Fig.16 [48]. In addition to the rotary and linear stators as well as a common mover coated with PMs, an actuator interface plate is adopted, which is beneficial to reduce the electromagnetic field coupling between the two modules. However, owing to the different structures of rotary and linear rotors, the travelling route is limited, resulting in its restricted applications.

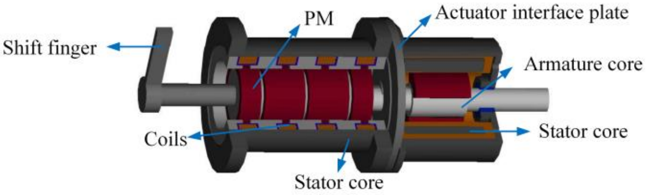


Fig.16. Direct-drive RL PM actuation module [48].

Another type of multi-stator 2DoF RL motor with independent RL magnetic fields is shown in Fig.17 [49], which is comprised of a three-phase 6/4 rotary SRM and a two-phase transverse flux linear SRM. The rotary and linear magnetic fields are produced by rotary and linear modules respectively. The fixed translators are adopted to reduce the mechanical coupling effect by avoiding the negative torque produced by the magnetic field induced in the translator. Apart from this, the main way to decouple the rotary and linear modules is realized by the decoupled control.

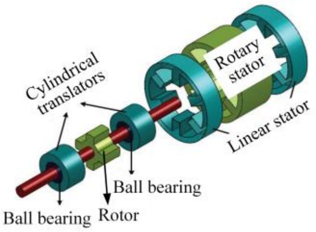
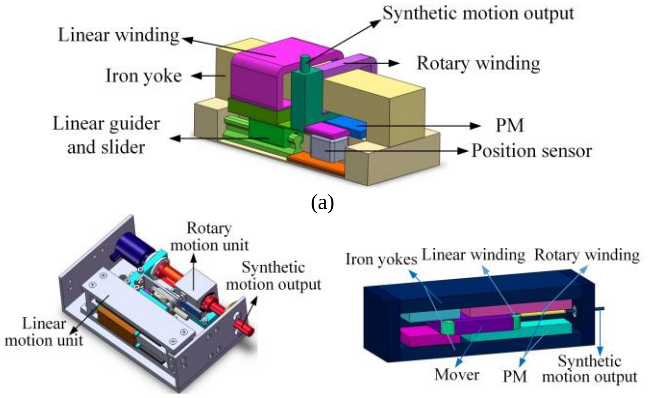


Fig.17. A RL SR motor [49].

On top of that, a novel 2DoF voice coil motor with independent magnetic fields was proposed [50], as shown in Fig.18 (a). The armature is composed of two windings which are respectively corresponding to the linear motion and rotary motion. Based on this, other two similar structures were proposed and analyzed [51], as shown in Fig 18 (b) and Fig.18 (c). It was concluded that the one with two independent magnetic fields for two motions units respectively (Fig 18 (b)) has perfect rotary torque features and a great controllability, due to the independent magnetic circuits in two motion units and its radial magnetic field in rotary motion unit [51, 52].



(a)

(b) (c)

Fig.18. A 2DoF voice coil motor [50-52]. (a) The voice coil motor with vertical axes of linear and rotary motion. (b) The voice coil motor with two motion units. (c) The voice coil motor with parallel axes of linear and rotary motions.

C. Summary

The researches of the topologies and the coupling effect of 2DoF RL motors are summarized as follows:

(1) There are varieties of topologies proposed by scholars, which can be applied to different kinds of applications according to their own advantages and disadvantages. For instance, short-stroke 2DoF RL motors with a mover of limited length can be applied to pick-put robots, etc.

(2) The existence of the coupling effect between rotary and linear modules is a universal phenomenon of 2DoF RL motors, which is mainly caused by cross RL magnetic field, end effect, two-motion interact of the common mover shared by two modules and so on.

(3) There will be magnetic field disturbances produced by the coupling effect when the motor produces rotary and linear motions at the same time, which leads to degradation of the motor performances.

(4) In general, the coupling effect in the motors with cross RL magnetic field is stronger than that in the motors with independent RL magnetic fields. It is on account of the shared magnetic circuit existing in the former but no close links of the rotary and linear magnetic fields in the later.

(5) Compared with the motors with independent RL magnetic fields, the motors with cross RL magnetic field are more integrated and smaller in size. However, the manufacture process of this type of motor is more complex and the corresponding control algorithms are more complicated.

(6) Most of the motors with cross RL magnetic field have longer linear stroke than those with independent RL magnetic fields, while SRM could be built with nearly infinite stroke with either crossed or independent magnetic fields.

(7) The analysis of the coupling effect is always based on FEM. In particular, 3D FEM is applied to model both 2DoF motions, which is accurate but time-consuming. In this case, the key problems to be solved in the investigations on 2DoF motors

are how to quantificationally analyze these coupling relationships and their effects on the controllability of the motor, and how to eliminate these undesirable effects.

Table I summarizes the qualitative comparison among the key issues of the two 2DoF RL motors.

TABLE I QUALITATIVE COMPARISON OF THE TWO 2DOF RL MOTORS

Items	The motors with crossed RL magnetic field	The motors with independent RL magnetic fields
Degree of coupling effect	higher	lower
Factors of coupling effect	cross RL magnetic field, end effect and two-motion interact of the common mover	end effect, two-motion interact of the common mover
Integrated level	higher integrated	integrated
Manufacturing process	complex	simple
Analyzing method	FEM (in general)	
Motor options (depending on operating principles)	induction motor, PM motor, SR motor, mixing-type motor, others	

IV. OPTIMIZATION DESIGNS OF 2DOF RL MOTORS

Although various topologies of the 2DoF RL motors have been proposed, the motor optimization objectives such as increasing the output torque or force, reducing the torque or force ripple, decreasing the copper losses and weakening the coupling effect are crucial for their developments. Moreover, in order to realize the commercial application of 2DoF RL motors, it is vital to find design-manufacturing methods with easy processes and low cost.

A. Increase of output torque or force

Compared with 2DoF RL induction motors, the output torque and thrust of 2DoF RL PM motors with the same structure parameters are higher in general [53]. So the two-armature RL PM motor based on the corresponding topology shown in Fig.3 was presented [54], as shown in Fig.19, which inherits the advantages of conventional PM machines.

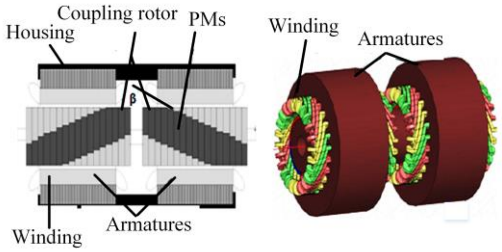


Fig.19. Two-armature RL PM motor [54].

In addition, for the 2DoF PM machines, the arrangement of PMs is a key factor influencing the electromagnetic performances. Based on the typical cross-coupled 2DoF motor (Fig.7), the Halbach magnet array was adopted. The optimized structure is shown in Fig.20 [55]. The length factor (the ratio of PM width to the polar distance) is determined based on FEM. It was found that the electromagnetic performances depend on the winding shape and the number of turns in the two helical windings. Apart from that, the disturbance produced by the coupling effect on force or torque can be reduced by optimizing the turns radio between the inner and outer windings. The optimization method can also be used in other 2DoF RL PM motors.

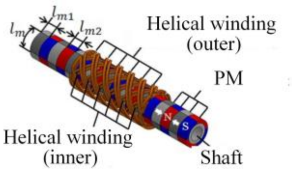


Fig.20 The optimized structure of the cross-coupled 2DoF motor [55].

Besides, the shape-changed stator model and thin back yoke (as shown in Fig.21) are applied to improve the torque-force characteristic of the 2DoF electromagnetic actuator shown in Fig.8 [56]. The linear ratio of torque-thrust characteristic is improved from 57.9% to 81.0% by using the proposed method.

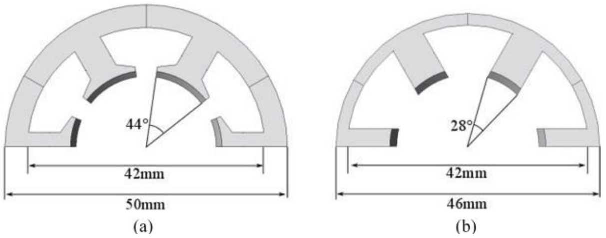


Fig.21. Changes for the stator of the 2DoF electromagnetic actuator [56]. (a) The conventional. (b) The shape-changed.

B. Reduction of torque or force ripple

Since the doubly salient structure is utilized, reducing torque or force ripple is a key problem for 2DoF RL PM and SR motors. The corresponding traditional optimization methods such as optimizing the combination of the slot and pole numbers and magnetic pole shape [57, 58] can also be applied to 2DoF RL motors. For example, the skew was applied to reduce the cogging torque of the 2DoF electromagnetic actuator shown in Fig.8 [56].

C. Decrease of losses

For the 2DoF zφ-module shown in Fig.22, a multi-physical framework, which contains coupling electromagnetic, mechanical, and thermal models, is implemented in MATLAB and used in the optimization procedure, which is performed with sequential quadratic programming [4]. The structure parameters, such as pole arc coefficient, coil opening angle, active length actuator, etc., were optimized to minimize the copper losses inside the rotary and linear actuators combined and the volume of the rotary actuator. In addition, due to the lower inertia, smaller moving mass, and higher magnetic loading, it was found that the configuration with moving coils produced 30% less copper losses than that with moving magnet.

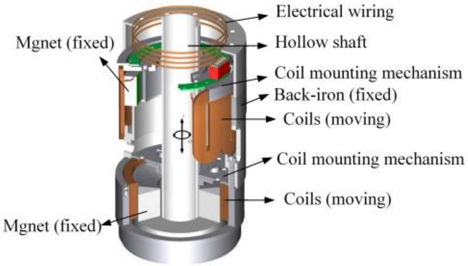


Fig.22. A 2DoF zφ-module [4].

D. *Weakening of coupling effect*

The weakening and elimination of coupling effect in 2DoF RL motors are difficult to accomplish. The corresponding decoupled control schemes are always applied to realize it. For example, for the 2DoF RL system shown in Fig.23 [21], an RC series circuit was connected in parallel with the terminals of the piezoelectric devices to compensate the self-EMF produced by the interference between the rotational and axial motions. In addition, the proportional control scheme was replaced with proportional and integral one. The positioning accuracy of the steady errors reduced from 27.5 ° to 0.05 ° for rotational motion and from 20.3 mm to 0.006mm for linear motion [59]. In addition, the method to add an auxiliary coil was also applied to a 3DoF magnetic bearing to reduce the cross-coupling effect, as shown in Fig.24 [60, 61].

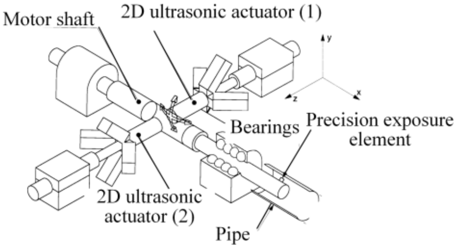


Fig.23. Schematic diagram of the RL motor [21].

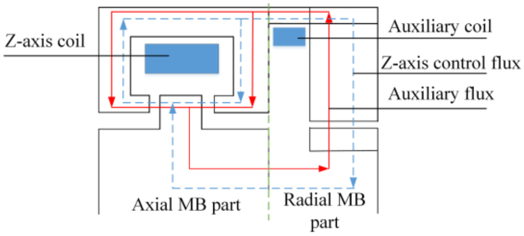


Fig.24. Position of auxiliary coil of a 3DoF magnetic bearing [60, 61].

E. *Simplification of manufacturing process*

Despite their appreciable application potential, the rather unconventional structures of some 2DoF RL motors are not suited to be properly manufactured using traditional processes that are already commonly used in the electromechanical industry. Therefore, how to manufacture a 2DoF RL motor in a low-cost and easy way is a key problem to solve for its commercial application. For instance, Silesian University of Technology in Gliwice carried out an intensive study [62, 63]. The authors presented an easy way, which was termed “transformation of structure” method, to construct a 2DoF 2-module induction motor (Fig.3 and Fig.15) using components of two factory-manufactured 3-phase squirrel-cage motors.

F. *Summary*

In general, the optimization design of 2DoF RL motors mainly focuses on two aspects. Firstly, based on the same RL topology arrangement, the rotary and linear parts can be replaced by other machines with different operation principles, respectively, including induction machines, PM machines, and SR machines as well as the mixture of them. Then the 2DoF motors will inherit the advantages of the corresponding conventional machines to adapt to varieties of applications. Secondly, the electromagnetic performances can be improved by utilizing the improved machine topologies, including using skew stator teeth, changing PM arrangement, and optimizing the key structure dimensions. However, as the inherent characteristic of the 2DoF RL motors, the coupling effect between the rotary and linear modules is difficult to be eliminated completely. At this stage, the mitigation of coupling effect is always realized by adopting corresponding decoupled control schemes except for the development of novel topologies.

Since the structure and shape of a 2DoF motor are obviously different from those of a conventional cylindrical motor, most of the equations, diagrams and graphs for designing a conventional motor are not likely to be suitable for designing a 2DoF motor. Therefore, a variety of optimization design methods are to be investigated in response to the characteristics of a 2DoF motor. Additionally, owing to the complex structure and difficult processing of a 2DoF motor, it is necessary to pay attention to the investigation on the manufacturing techniques of 2DoF motors.

V. DECOUPLED CONTROL SCHEMES OF 2DOF RL MOTORS

The 2DoF RL motor is a typical electromechanical integration products, thus it is difficult to achieve accurate and effective control by using the traditional control algorithms, especially for the motors with crossed RL magnetic field. Therefore, it is necessary to develop suitable decoupling algorithms for 2DoF RL motors control systems.

Compared with the 2DoF RL motors with crossed RL magnetic field, the control schemes of motors with independent RL magnetic fields are much easier. However, although the later can be realized by independent control of rotary and linear motions based on traditional control algorithms [7], high-accuracy control is hard to achieve unless the coupling effect of the two modules is fully considered. For example, a triple closed-loop control system including the position-loop, speed-loop and current-loop were applied to the voice coil motor shown in Fig.18 (a). Moreover, the fuzzy control and feedforward control were also provided. As a result, the rise time of the position and the compound position following error rate reduced to 1.3ms and 0.43‰, respectively [7].

For the 2DoF RL motors with crossed RL magnetic field, some decoupled control schemes were proposed. A novel two-directional d-q transformation based on the current hysteresis for the RL Halbach PM actuator (shown in Fig.14) was proposed, which was used to decouple the inter-relationship between the current and voltage in each coil mentioned above [46]. Fig.25 shows the two-directional d-q transformation, in which the general d-q transformation is used in the z and θ directions simultaneously. The block diagram of dual d-q controller is shown in Fig.26. Based on this proposed model, decoupled control is realized by assuming some current components in the mover frame are zero and both the simulated and experimental results validate the effectiveness, as shown in Fig.27.

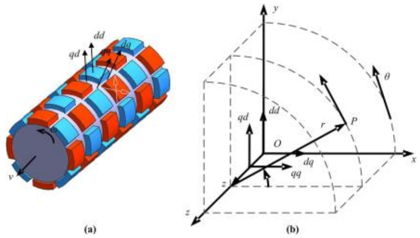


Fig. 25. Two-directional d-q transformation [46]. (a) Four d-q axis system. (b) Cylinder coordinate system and mover frame of the RL Halbach PM actuator.

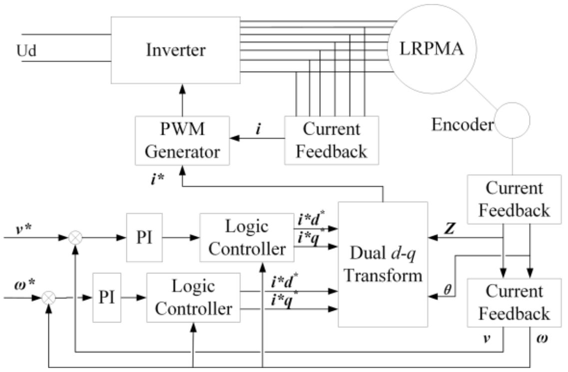


Fig.26. Block diagram of dual d-q controller [46].

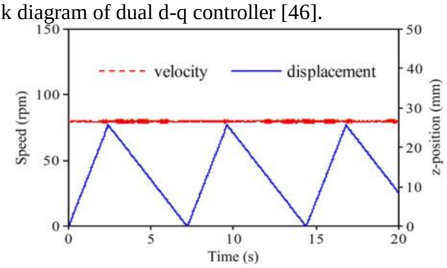


Fig. 27. Simulation displacement and velocity results of helical movement [46].

In addition, the authors in [1, 11] proposed a decoupling control strategy for the RL SR motor shown in Fig.11. The torque and force distribution functions (TFDF) of two separated stator parts were deduced respectively, which are determined by the 3-phases inductances and current values with respect to the linear and the angular positions. Based on the multiphase excitation method, the decoupling control can be realized by the TFDF scheme as shown in Fig.28. The results showed that the motor was capable of high-precision rotary and linear position tracking with the steady error within 0.3° and 10 μm, respectively.

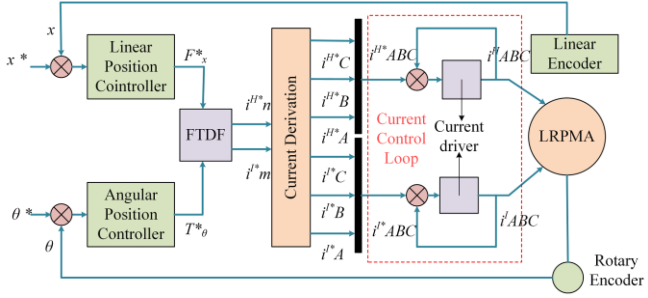


Fig.28. The decouple control scheme of the RL SR motor[11].

For the 2DoF RL SR motor with multi-stator shown in Fig.12, the realization of rotary and linear motions is based on the classical control of SR motor, and the current in each phase per stator stack is controlled independently. The corresponding phase current values are determined by the special sequences of the windings' feedings, which depends on the angular and linear positions of mover. The simulation results demonstrated the effectiveness of the proposed scheme on the decoupling of rotary and linear magnetic fields [28].

In addition, the control scheme with the variables of rotary speed and torque, linear speed and position was proposed by P. Bolognesi. The intermediate separated velocity loops were used for the regulation of the angular and axial speed of the 2DoF RL motor shown in Fig.13(a) [33]. The control scheme using minimum resistive losses criterion was also implemented for the motor shown in Fig.13(b) [34]. The simulation results, such as the electromagnetic torque and force, the angular and axial positions, etc., confirmed the conceptual possibility to obtain effective rotary-linear drives.

In general, a 2DoF motor typically belongs to a category of mechatronics products. The drive control system of a 2DoF motor not only needs to measure position, speed, acceleration and output torque or thrust force of each degree of freedom, but also carry out the decoupling calculation and locus planning among different degrees of freedom. Therefore, it is necessary to develop special control algorithms based on the detailed structure of the motor, deeply analyze the coupling relationships among different degrees of freedom, and investigate the mechanical decoupling control strategies, thus improving the steady and dynamic performances, and increasing the stability of the motor.

VI. CONCLUSION

The ongoing effort to replace the traditional bulky 2DoF RL mechanical system by a single 2DoF RL motor has led to improved reliability, maintainability and cost effectiveness. However, time is needed to realize its commercial application at this stage. This paper has presented an overview of the 2DoF RL motor with emphasis on the topologies as well as the corresponding coupling effect, the optimization designs and manufacturing methods, control algorithms especially for the decoupling control. It can be concluded as following.

(1) The 2DoF RL motors have a huge potential in intelligent applications, including robots, automobiles and so on, due to their integrated structures, saving material, easy maintenance, etc.

(2)The coupling effect between the rotary and linear modules, which will deteriorate the quality of the output torque or force, cannot be ignored.

(3)The future work for this kind of motors should concentrate on the novel motor topologies, development of the theoretical analyzing methods, minimization of coupling effect, advanced decoupling control algorithms, and low-cost manufacturing schemes as well as more applications.

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