Feasibility evaluation of new electric motors driven by intrinsic localized mode

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Abstract: Intrinsic localized mode (ILM) has been observed in various physical systems. In particular, electromagnetic ILM has been observed on an LC ladder circuit array. This paper focused on the electromagnetic ILM and aims to evaluate the feasibility of a new electric motor driven by the electromagnetic ILM numerically. First, we propose two types of nonlinear inductors with different geometries, and their magnetic saturation characteristics are clarified from the magnetic field analysis. Second, numerical simulations using the obtained parameters show that the moving velocity of a moving ILM varies with an initial voltage disturbance. Finally, we propose an inductor with permanent magnets placed on a surface of a rotor core, aiming to generate the electromagnetic ILM more efficiently. Numerical simulations show that the behavior of the moving ILM is affected by the rotational speed of the rotor.

Key Words: electric motors, intrinsic localized mode, LC ladder circuit, magnetic saturation, nonlinear inductance

1. Introduction

Intrinsic localized mode (ILM), which is also called discrete breather (DB), is the spatially localized and time-periodic oscillation induced by the discreteness and nonlinearity of the system. The existence of ILM was found in 1988 by Takeno and Sievers [1, 2]. Many researchers have been interested in ILM because it has unique characteristics which are not observed in a linear dynamical system. ILM has been observed analytically, numerically, and experimentally. In particular, the ILM has been experimentally observed at various scales from micrometer to meter sizes [3–5]. However, the following question is very important and fundamental for engineering/industrial applications of the ILM: “How is the localized energy picked out into the external system and used?” As one of the answers, we focus on electrical machines such as motors, actuators, transformers, sensors, especially electric motors.

There are two most important nonlinear problems in electric motors. One is the magnetic satu-
tion phenomenon of soft magnetic materials, and the other is the hysteresis property of soft magnetic materials. Magnetic saturation is a phenomenon in which the magnetic flux density reaches a maximum even if the applied magnetic field is increased. Magnetic saturation causes undesirable changes in parameters such as coil inductance and torque constant of a motor. Therefore, the magnetic saturation should generally be avoided when designing an efficient and robust electric motor. The hysteresis property is the dependence of the magnetic flux density on its history. When the alternating magnetic field is applied to soft magnetic materials, the magnetic hysteresis occurs and the magnetic energy is consumed as a thermal energy corresponding to a hysteresis loop.

Three-phase AC voltage is commonly used to operate electric motors. A sinusoidal voltage is applied to three sets of coils with a phase shift of 120 degrees to produce a rotating magnetic field. This rotating magnetic field behaves like a kind of plane wave, with the frequency corresponding to the rotational speed of the motor/rotor and the wave number corresponding to the number of poles of the rotating magnetic field.

In other words, the rotating magnetic field is similar to moving ILM in terms of moving energy. This suggests that the electromagnetic ILM excited on an electrical circuit could be used as a new principle of operation of AC motors.

In this paper, we first describe an LC ladder circuit consisting of a nonlinear inductor and a capacitor. Second, we propose two types of nonlinear inductors with different geometries and their magnetic saturation characteristics are clarified from the magnetic field analysis based on the two-dimensional finite element method. Third, Numerical simulations using the obtained parameters show that a moving ILM is generated in both inductors, and its moving speed varies with the magnitude of the initial voltage disturbance. Finally, we propose an inductor with permanent magnets placed on the surface of the rotor core, aiming to generate ILM more efficiently. Numerical simulations using a two-dimensional look-up table obtained from magnetic field analysis show that the behavior of the moving ILM is affected by the rotational speed of the rotor.

2. Nonlinear LC ladder circuit array

2.1 Analogy between mechanical and electrical system

It is well known that LC circuits have a mathematical structure similar to that of mass-spring systems. The nonlinear spring force in the mechanical system corresponds to the nonlinear capacitance in the electrical system. Although some previous studies have succeeded in realizing a nonlinear capacitor by applying a reverse bias voltage to a diode [6], tuning its nonlinear characteristics was not easy. Instead of making the capacitor nonlinear, the electromagnetic ILM is excited thanks to a nonlinear inductor. The nonlinearity of the self-inductance can be easily achieved by using magnetic saturation phenomenon of soft magnetic materials such as electrical steel sheet (ESS) [7]. Moreover, the nonlinear inductance characteristics can be adjusted by various parameters such as the selection of the soft magnetic material, dimensions, and the shape of the inductor, and so on. The magnetic saturation of the inductor is equivalent to lighten mass in the mechanical system. As a result, the apparent spring becomes harder and the ILM is successfully excited.

Figure 1 shows the circuit diagram for the LC ladder circuit array in which inductors and capacitors

\[ I_{n-1} \rightarrow C \rightarrow \ldots \rightarrow C \rightarrow I_n \rightarrow Q_{n-1} \rightarrow C \rightarrow \ldots \rightarrow C \rightarrow I_{n+1} \]

Fig. 1. Circuit diagram for LC ladder circuit array with linear capacitors C and nonlinear inductors.
are interconnected such as a ladder. Here, we define the time integral of the difference between \((n+1)\)th and \(n\)th inductor currents as the charge of the \(n\)th capacitor, as follows:

\[
Q_n = \int (I_n - I_{n+1}) dt.
\]  

(1)

The nonlinear inductor is designed so that the magnetic flux linkage becomes a cubic function of the current. We can assume that the mutual inductance is tiny and negligible when a magnetic flux path of the inductor is closed. The relationship between the current through the \(n\)th inductor \(I_n\) and the magnetic flux \(\phi_n\) can be expressed using the parameter \(\beta\) that represents the magnitude of magnetic saturation [8, 9],

\[
I_n = \frac{1}{L_0} \phi_n + \frac{\beta}{L_0 n_c^3} \phi_n^3.
\]  

(2)

Here, \(L_0\) is the linear component of the self-inductance, and \(n_c\) is the number of turns of the coil. From Kirchhoff’s voltage law, the following loop equation on \(n\)th magnetic flux \(\phi_n\) is obtained:

\[
d\phi_n/dt = -Q_n/C + Q_{n-1}/C = -1/C \int (2I_n - I_{n+1} - I_{n-1}) dt.
\]  

(3)

Substituting Eq. (2) into the time derivative of Eq. (3) results in a second-order differential equation on \(n\)th magnetic flux \(\phi_n\):

\[
d^2 \phi_n/dt^2 = -\omega_m^2/4 (2\phi_n - \phi_{n+1} - \phi_{n-1}) - \beta \omega_m^2/4n_c^3 (2\phi_n^3 - \phi_{n+1}^3 - \phi_{n-1}^3),
\]  

(4)

where \(\omega_m^2 = 4/(L_0 C)\). The second term on the right side is a nonlinear on-site term caused by magnetic saturation of the inductor. The obtained differential equation here is slightly different from that of FPU-\(\beta\) lattice. Nevertheless, it is reported that the electromagnetic ILM is excited thanks to the nonlinear on-site term [9].

2.2 Design of magnetic saturation property

In this subsection, the magnetic saturation characteristics of inductors are designed in a real scale. The magnetic circuit method [10] and the finite element method [11] are often used for the design of magnetic circuits. The magnetic circuit method calculates the amount of magnetic flux from the magnetomotive force and magnetic resistance. This method is effective in the region where the magnetic permeability of soft magnetic materials is constant. Since nonlinear inductors operate in the magnetic saturation region, it is difficult to design their magnetic saturation characteristics using the magnetic circuit method. Therefore, in this paper, the magnetic saturation characteristics of the inductor are designed from the electromagnetic field analysis based on the two-dimensional finite element method, and the magnetic flux distribution is visualized.

2.2.1 Straight array type

Figure 2 shows the basic configuration of the straight array type inductor. This consists of stator core, mover core, and excitation coil. The stator core and mover core are made of electrical steel sheet (50JN470, JFE Steel) which is laminated in the axial direction. The coil (150 turns) is wound in a circumferential direction. Since this inductor has an axisymmetric structure, a two-dimensional model shown in Fig. 2(b) is sufficient for evaluating magnetic saturation property of the inductor through electromagnetic field analysis.

Figure 3 shows the computed nonlinear relationship between the applied current and the magnetic flux across the coil. The solid line in Fig. 3 is the approximated cubic function corresponding to Eq. (2). Figure 3 shows that the desired magnetic saturation characteristics can be achieved by designing the magnetic circuit of the inductor appropriately. Figure 4 shows the contour diagrams for magnetic flux density distribution of straight array type inductor. When the applied current reaches 5.0 A, magnetic saturation occurs at the center of the mover core due to its thin radial width. Furthermore, the magnetic flux due to the applied current mainly passes through the iron core, and
the leakage flux into surrounding air region is tiny enough to neglect the mutual inductance between adjacent inductors. These results suggest that the magnetic saturation characteristic of the nonlinear inductor can be designed by two-dimensional electromagnetic field analysis, and the state of magnetic saturation can be visualized by a post-process.

2.2.2 Annular array type
Figure 5 shows the basic configuration of the array array type inductor. This consists of stator core, rotor core, and excitation coil. The stator core and rotor core are made of electrical steel sheet (50JN470, JFE Steel) which is laminated in the z-axis direction. The axial length of the inductor is 50 mm. The coil is wound around the stator core. As in the straight array type, a closed magnetic path is formed to prevent magnetic flux from leaking into adjacent inductors.
circuit is formed so that the effect of mutual inductance can be eliminated. If the annular inductors are arranged in the circumferential direction, the total number of inductors becomes 20. However, since the inductors form a closed magnetic path, they can be placed intermittently in the circumferential direction. In this case, the total number of inductors becomes less than 20.

Figure 6 shows the computed nonlinear relationship between the applied current and the magnetic flux across the coil for annular array type inductor. The solid line in Fig. 6 is the approximated cubic function corresponding to Eq. (2). Figure 7 shows the contour diagrams for magnetic flux density distribution for annular array type inductor. When the applied current reaches 5.0 A, magnetic saturation occurs inside the stator core. The magnetic flux due to the applied current mainly passes through the iron core, and the leakage flux into surrounding air region is tiny enough to neglect the mutual inductance between adjacent inductors, as we expected.

![Fig. 5. Basic configuration of annular array type inductor. (a) Main dimension (Unit: mm). A closed magnetic path is formed to prevent magnetic flux from leaking into adjacent inductors. (b) Two-dimensional finite element mesh. The mesh size in the air gap is sufficiently small to calculate variation of magnetic flux density accurately.](image1)

![Fig. 6. Computed relationship between the applied current and the magnetic flux across the coil (annular array type inductor).](image2)

![Fig. 7. Contour diagram for magnetic flux density distribution for annular array type inductor. Applied current $I = 1.0, 3.0, 5.0$ A. When the applied current reaches 5.0 A, magnetic saturation occurs inside the stator core.](image3)
2.3 Numerical simulation of electromagnetic ILM on LC ladder circuit array

The results of the previous section show that magnetic saturation characteristics can be achieved by using soft magnetic materials to construct inductors, regardless of the geometry and dimensions of the inductor. In this section, numerical simulation with identified parameters reveals the generation of electromagnetic ILM, i.e., localized magnetic flux density distribution, by placing several designed nonlinear inductors and interconnecting them with linear capacitors.

2.3.1 Straight array type

As shown in Fig. 3, the current of a straight array type inductor can be approximated as a cubic function of the magnetic flux. From this approximate curve, the inductor is identified as $L_0 = 11.8 \text{ mH}$ and $\beta = 5.9 \times 10^9 \text{ Wb}^{-2}$ based on Eq. (2). Although the results of the magnetic field analysis are used to identify the parameters of the inductor, it should be noted that this section does not implement the coupled analysis with the magnetic field analysis and the numerical simulation. The LC ladder circuit, ignoring the internal resistance of the inductors and capacitors, is a Hamiltonian-preserving system with a Hamiltonian of the form

$$H = \sum_{n=1}^{N} \left( \frac{1}{2} L_0 \phi_n^2 + \frac{\beta}{4 L_0 C \alpha} \phi_n^4 \right) + \sum_{n=1}^{N} \frac{1}{2} C V_n^2. \quad (5)$$

Here, $N$ is the number of LC ladder circuit units, $V_n$ is the voltage drop across the $n$th capacitor. Equation (5) indicates the generalized coordinates are the magnetic flux of the inductor $\phi$ and the voltage drop across the capacitor $V$. We apply a 6th order symplectic integrator to preserve the Hamiltonian. Figure 8 shows the spatiotemporal plot of static ILM (ST-mode). The ladder size $N = 51$ and the capacitance $C$ is unified to 100 $\mu$F. The initial magnetic flux $\phi(0)$ is determined from the method presented in [9]. It does not give the exact static ILM solution. However, this is a good guess for the ILM with the desired frequency. $\lambda$ shown in this figure is the dimensionless parameter $\lambda = 4\beta \alpha^2 / 4n_0^3$ where $\alpha$ is the initial magnetic flux of the center inductor. The static ILM persists for a long time, with slight dissipation to neighboring lattices. The observed internal vibration frequency is approximately 384.6 Hz. At this frequency scale, the eddy current loss due to the magnetic flux density change in ESS is almost the same as that of general electric motors.

Figure 9 shows the spatiotemporal plot of moving ILM for three different initial voltage conditions $V_{26\pm1}(0) = \pm 5, \pm 10, \pm 15$ V. Here, $V_n(0)$ is the given voltage drop across the $n$th inductor at 0 s. This figure suggests that the magnitude of the applied disturbance is related to the translational velocity of the moving ILM. We have not found the analytical reason why the translational speed depends

![Fig. 8. Spatiotemporal plot of static ILM (ST-mode) when the straight array type inductors are employed in the LC ladder circuit array. The ladder size $N = 51$ and the initial magnetic flux $\phi(0)$ was determined from the method presented in [9]. The method does not give the exact static ILM. However, this is a good guess for ILM with the desired frequency.](image-url)
Fig. 9. 2-D spatiotemporal plot of moving ILM for three different initial voltage conditions when the straight array type inductors are employed in the LC ladder circuit array ($V_{2k\pm 1}(0) = \pm 5, \pm 10, \pm 15$ V).

on the initial voltage yet. The dependence is expected to be related to the vibrational energy stored in the initial state ILM. In order to evaluate the velocity, the energy distribution of each LC circuit unit is calculated. The energy stored in the nth LC circuit unit is defined by

$$e_n = \frac{1}{2}L_0 \phi_n^2 + \frac{\beta}{4L_0 n_c^4} \phi_n^4 + \frac{1}{2}CV_n^2.$$ \hfill (6)

The center position of moving ILM $x(t)$ is defined by

$$x(t) = \frac{\sum_{n=1}^{N} n e_n}{\sum_{n=1}^{N} e_n}.$$ \hfill (7)

Figure 10 shows the average center position $x(t)$ of the localized magnetic flux distribution for the three conditions above. The speed of the moving ILM is slightly fluctuating non-periodically. This is probably because the initial value of the moving ILM is different from an exact periodic solution calculated from iteration method such as the Newton method. Nevertheless, it is possible to move the ILM roughly proportionally depending on the magnitude of the initial voltage. Therefore, there is a possibility of constructing a new linear synchronous motor in which the mover moves synchronously with the traveling magnetic field created by the electromagnetic moving ILM.

Next, two-dimensional magnetic field analysis is implemented to visualize the magnetic flux density distribution when the ILM is moving. The current flowing in each inductor is calculated based on

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**Fig. 10.** Center position $x(t)$ of the localized magnetic flux for the three different conditions.
Eq. (2) from the magnetic flux time series data of each inductor shown in Fig. 9. Then, the magnetic flux density vector distribution is visualized by the current input analysis. Figure 11 visualizes the magnetic flux density distribution of the straight array when $V_{26\pm1} = \pm10$ V. Since the magnetic flux density distribution is well localized, only the 11 inductors near the center inductor are considered in the magnetic field analysis. This figure displays only the seven inductors with particularly high flux density. It can be confirmed that the moving ILM is moving at approximately constant speed and magnetic saturation occurs at the center of the mover core, as we visualized in Fig. 4.

### 2.3.2 Annular array type

As shown in Fig. 6, the current of annular array type inductor can be approximated as a cubic function of the magnetic flux. From this approximate curve, the inductor is identified as $L_0 = 1.48$ mH and $\beta = 1.7 \times 10^{10}$ Wb$^{-2}$ based on Eq. (2). Figure 12 shows the spatiotemporal plot of moving ILM (ST-mode) for three different initial voltage conditions ($V_{6\pm1} = \pm1, \pm2, \pm3$ V). Although straight and annular array type inductors are common in using their magnetic saturation, they are completely different in their geometries. This is the reason why their initial voltage conditions are different. The ladder size $N = 20$ and the capacitance $C$ is unified to 100 $\mu$F. The initial magnetic flux $\phi(0)$ is determined from the method mentioned in the previous section. The moving ILM moves at almost constant velocity, with slight dissipation to neighboring lattices. The observed internal vibration frequency is approximately 909 Hz. At this frequency scale, the eddy current loss due to the magnetic

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**Fig. 11.** Time revolution of magnetic flux density vector distribution for straight array type. Since the magnetic flux density distribution is well localized, only the 11 inductors near the center inductor are considered in the magnetic field analysis. In this figure, only the seven inductors with particularly high flux density are displayed.

**Fig. 12.** 2-D spatiotemporal plot of moving ILM for three different initial voltage conditions when the annular array type inductors are employed in the LC ladder circuit array ($V_{6\pm1} = \pm1, \pm2, \pm3$ V).
flux density change in ESS is almost the same as that of general electric motors.

Figure 13 shows the average center position $x(t)$ of the localized magnetic flux distribution for the three initial voltage conditions ($V_{0\pm1} = \pm1, \pm2, \pm3$ V). The speed of the moving ILM is slightly fluctuating non-periodically. This is probably because the initial value of the moving ILM is different from an exact periodic solution calculated from the iteration method. Nevertheless, this result implies that the rotation speed of the moving ILM can be controlled by the magnitude of the applied voltage disturbance. For example, when $V_{0\pm1} = \pm2$ V, the moving ILM rotates $144 \times 8 = 18 \times 8$ degree in 0.1 s. The rotational speed is converted into 240 round per minute (rpm). Next, two-dimensional magnetic field analysis is implemented to visualize the magnetic flux density distribution when the ILM is moving in the circumferential direction. The current flowing in each inductor is calculated based on Eq. (2) from the magnetic flux time series data of each inductor shown in Fig. 12. Then, the magnetic flux density vector distribution is visualized by the current input analysis. Figure 14 visualizes the magnetic flux density distribution of the annular array when $V_{26\pm1} = \pm2.5$ V. It can be seen that the moving ILM is rotating counterclockwise at a roughly constant speed.

![Graph of Figure 13](image1.png)

**Fig. 13.** Center position $x(t)$ of the localized magnetic flux for the three different conditions (annular array type).

![Graph of Figure 14](image2.png)

**Fig. 14.** Magnetic flux density distribution for annular array type.
3. Feasibility of surface permanent magnet synchronous motors driven by moving ILM

In the previous section, both straight and annular type inductor consisted of ESS and coil. However, in practical use, it is expected that the ILM can be rotated efficiently by using permanent magnets to increase the magnetic energy of the magnetic circuit. In this section, we present a surface permanent magnet (SPM) synchronous motor driven by moving ILM and evaluate its feasibility through numerical simulation using 2-D look-up tables obtained from the magnetic field analysis.

3.1 Basic structure

Figure 15 shows the basic configuration of the potential SPM synchronous motor proposed in this paper. The number of magnet pole pairs \( N_{pm} \) is set to 20. The number of inductors \( N \) is also 20. General electric motors do not coincide. All coil winding directions are uniform. The N and S pole magnets (N42SH) are magnetized in the radial directions and their remanences are 1.4T. It is well known that in a typical electric motor, the number of pole pairs of permanent magnets should not match the number of slots (the number of coils) because this condition does not generate any torque. In this paper, we assume the SPM motor with \( N = N_{pm} \) as an fundamental consideration.

![Fig. 15. Surface permanent magnet (SPM) synchronous motor driven by moving ILM. (a) Overall view. In this case, the number of magnet pole pairs is set to 20. All coil winding directions are uniform. (b) Enlarged view. The N and S pole magnets (N42SH) are magnetized in the radial directions and their remanences are 1.4T.](image)

3.2 Nonlinear inductance property obtained from 2-D FEA

This SPM type inductor is characterized by the variation of magnetic flux across the coil by the permanent magnet depending on the rotor angle. Therefore, its complex magnetic saturation characteristics are clarified by two-dimensional magnetic field analysis. Figure 16 shows the analyzed nonlinear inductance characteristics under the three different rotor angle (\( \theta = 0, 4.5, 9 \) degree). When \( \theta = 4.5 \) degree, the nonlinear inductance becomes symmetrical with respect to positive and negative current variation. In other words, the SPM inductor at 4.5 degree operates similarly to the straight and annular array type shown in the previous section. When \( \theta = 0, 9 \) degree, on the other hand, the nonlinear inductance becomes asymmetrical with respect to positive and negative current variation. These properties cannot be modeled by odd functions and can no longer be expressed by the cubic function in Eq. (2).

These complex magnetic saturation characteristics is understood by visualizing the magnetic flux density distribution in the stator and rotor cores. Figure 17 shows the magnetic flux density distribution of the SPM type inductor for nine different conditions.

3.2.1 \( \theta = 4.5 \) degree

When the applied current \( I = 0 \) A, the magnetic flux from the magnet does not pass through the stator core since the permanent magnets are aligned at the midpoint of the stator core. In this
Fig. 16. Computed relationship between the applied current and the magnetic flux across the coil with respect to the rotor angle. The magnetic flux by permanent magnets is subtracted to investigate only the nonlinear inductance characteristics.

Fig. 17. Magnetic flux density distribution of SPM inductor. The minimum and maximum flux density (0.0 and 2.0 T) corresponds to blue and red in the color map, respectively.

case, magnetic saturation does not occur at the stator core. As the applied current increases, the magnetic saturation occurs and the magnetic flux does not increase easily. Because this tendency is independent of the positive or negative current, the relationship between magnetic flux and current can be approximated by an odd function.

3.2.2 $\theta = 0, 9$ degree
When the applied current $I = 0$ A, the magnetic flux from the magnet pass through the stator core since the permanent magnets are facing the stator core. This causes magnetic saturation in the stator core when the current is not applied. Note that the magnetic flux distributions at 0 and 9 degree look similar but the directions of the flux are opposite. As the applied current increases, the magnetic saturation is eliminated at 0 degree, while it becomes stronger at 9 degree. This is the reason why the
Three-dimensional surface plot of magnetic flux with respect to the applied current and the rotor angle. Because of the circumferential periodicity, the magnetic flux characteristics are symmetric with respect to the positive and negative angular variations.

3.3 Numerical simulation using 2-D look-up table

From the results of Fig. 16, it is expected that the differential equation of the LC ladder circuit with SPM inductor becomes severely complicated than that of the FPU-β lattice. Since it is very difficult to obtain the exact solution of the ILM analytically, we clarify the behavior of the moving ILM from numerical simulations using a two-dimensional look-up table (LUT). Figure 18 shows the three-dimensional surface plot of the magnetic flux with respect to the applied current and the rotor angle. Because of the circumferential periodicity, the magnetic flux characteristics are symmetric with respect to the positive and negative angular variations.

The differential equation of the LC ladder circuit consisting of the SPM type inductors and linear capacitors is expressed as follows:

$$\frac{d^2 \phi_n}{dt^2} = -\frac{1}{C}(2f(\phi_n, \theta) - f(\phi_{n-1}, \theta) - f(\phi_{n+1}, \theta)).$$

(8)

Here, $f$ is the 2-D LUT shown in Fig. 18. Spline interpolation is applied to make the known data points continuous. In this section, we verify whether moving ILM remains stable even when the rotor is rotating. If this is clarified, the possibility of the new AC motor will become apparent. We assume the rotational speed $v_r$ is constant and the rotor is forced to rotate by a certain external torque. Figure 19 shows the center position of the moving ILM for different rotational speeds of the rotor. When $v_{rotor} = 0$ rpm, the rotational speed of the moving ILM $v_{ILM}$ is approximately 600 rpm. In order for the ILM to operate as an electric motor, the moving ILM must be synchronized with the rotor speed. However, when $v_{rotor}$ is 600 rpm, the moving ILM cannot maintain its rotational speed and is not synchronized with the rotor motion. On the other hand, when $v_{rotor}$ is smaller than 300 rpm, the effect of rotor motion on the behavior of the moving ILM is tiny. Thus, the moving ILM in the SPM type inductor is sensitive to the parameters, and further detailed investigation is required in the near future.

4. Conclusions

This paper evaluated feasibility of a new electric motor driven by intrinsic localized mode (ILM). First, we described an LC ladder circuit consisting of a nonlinear inductor and a capacitor. Second, we proposed two types of nonlinear inductors with different geometries: straight array type and annular
array type inductor. Two-dimensional finite element analysis revealed that the desired magnetic saturation characteristics can be achieved regardless of the geometry of the inductor. Third, numerical simulations using the obtained parameters showed that a moving ILM was generated in both inductors, and its moving speed varied with the magnitude of the initial voltage disturbance. Additionally, we visualized the translational or rotating behavior of the localized magnetic flux distribution through finite element analysis. Finally, we proposed a surface permanent magnet type inductor, aiming to generate ILM more efficiently. Numerical simulations using a two-dimensional look-up table clarified that the behavior of the moving ILM was affected by the rotational speed of the rotor.

The new AC motor driven by the moving ILM is feasible because its dynamical behavior is similar to a rotating magnetic field generated by a three-phase AC. Although it is difficult to mention the specific power rating and operational frequency, the power rating and operational speed are estimated to be in the range of 100–1000 W and several hundred or thousand rpm from Figs. 5 and 13, respectively. In particular, a further investigation is necessary on a magnitude of output torque produced by the moving ILM.

Simplification of a three-phase PWM inverter circuit is one of the most promising advantages to use the moving ILM as an operational principle of typical three-phase AC motors. They are driven by the three-phase PWM inverter. It switches the direction of the three-phase current and results in the generation of the rotating magnetic field. This indicates that the three-phase PWM inverter is indispensable for the variable torque/speed operation of three-phase AC motors. On the other hand, the moving ILM moves “spontaneously” or “autonomously” across the LC ladder circuit array. Because it no longer needs to switch three-phase current, the rotating magnetic field by the moving ILM is expected to simplify the PWM inverter.

Although this paper has not been able to verify the operation of a new motor using a surface permanent magnet type inductor, further verification is necessary in the near future because the shape or topology of the inductor is not limited to the ones described in this paper. Besides, we plan to fabricate a prototype of the annular array type inductor and observe the generation of a moving ILM experimentally.

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References
[1] S. Takeno, K. Kisoda, and A.J. Sievers, “Intrinsic localized vibrational modes in anharmonic crystals,” Progress of Theoretical Physics Supplement, no. 94, pp. 242–269, 1988.
[2] A.J. Sievers and S. Takeno, “Intrinsic localized modes in anharmonic crystals,” Phys. Rev. Lett., vol. 61, no. 8, pp. 970–973, 1988.

[3] M. Sato, B.E. Hubbard, and A.J. Sievers, “Observation of locked intrinsic localized vibrational modes in a micromechanical oscillator array,” Physical Review Letters, vol. 90, no. 4, 044102, January 2003.

[4] M. Kimura and T. Hikihara, “Coupled cantilever array with tunable on-site nonlinearity and observation of localized oscillations,” Physics Letters A, no. 373, pp. 1257–1260, February 2009.

[5] Y. Watanabe, M. Nishimoto, and C. Shiogama, “Experimental excitation and propagation of nonlinear localized oscillations in an air-levitation-type coupled oscillator array,” Nonlinear Theory and Its Applications, IEICE, vol. 8, no. 2, pp. 146–152, April 2017.

[6] S. Shige, K. Miyasaka, W. Shi, Y. Soga, M. Sato, and A.J. Sievers, “Experimentally observed evolution between dynamic patterns and intrinsic localized modes in a driven nonlinear electrical cyclic lattice,” EPL, vol. 121, no. 3, 30003, April 2018.

[7] JFE Steel Corporation, Non-oriented electrical steel sheet, https://www.jfe-steel.co.jp/en/products/electrical/product/n_core.php, accessed 1 April 2021.

[8] Y. Ueda, “Random phenomena resulting from non-linearity in the system described by Duffing’s equation,” Int. J. of Non-Linear Mechanics, vol. 20, no. 5–6, pp. 481–491, 1985.

[9] M. Sato, T. Mukaide, T. Nakaguchi, and A.J. Sievers, “Inductive intrinsic localized modes in a one-dimensional nonlinear electric transmission line,” Phys. Rev. E, no. 94, 012223, July 2016.

[10] TDK Corporation, Magnetic Circuit Design Guide, https://product.tdk.com/en/products/magnet/technote/designguide.html, accessed 1 April 2021.

[11] M. Kato, Y. Kono, K. Hirata, and T. Yoshimoto, “Development of a haptic device using a 2-DOF linear oscillatory actuator,” IEEE Transaction on Magnetics, vol. 50, no. 11, 8206404, November 2014.