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## PERIODIC SOLUTIONS OF THE SPATIAL EXTENSION OF A CONDITIONALLY PERIODIC SYSTEM

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**ABSTRACT.** We consider a linear system of differential equations  $x' = a(t)x - \mu x$  with a conditionally periodic matrix  $a$  and a parameter  $\mu \in \mathbb{C}$ . We prove that there exists a nonempty set  $M \subset \mathbb{C}$  such that for each  $\mu \in M$  the spatial periodic extension of this system, which is a system of first order partial differential equations, has a generalized (in the framework of Schwartz's theory of distributions) periodic solution.

**Keywords:** conditionally periodic system, quasi-periodic solution, periodic Schwartz's distribution, linear homogenous system.

### 0. INTRODUCTION

**0.1.** Consider the system of differential equations

$$x' = a(t)x - \mu x \tag{0.1_\mu}$$

with a real conditionally periodic matrix  $a(t) = A(et)$ , where  $A = A(\varphi)$  is a continuous  $\omega_j$ -periodic in  $\varphi_j$  ( $j=1, \dots, m$ )  $n \times n$ -matrix function,  $\varphi = (\varphi_1, \dots, \varphi_m) \in \mathbb{R}^m$ ,  $\omega = (\omega_1, \dots, \omega_m)$ ,  $e = (1, \dots, 1) \in \mathbb{R}^m$  (not to be confused with the Euler number  $e$ ),  $t \in \mathbb{R}$ ,  $\mu \in \mathbb{C}$ , and the frequencies  $\beta_i = 2\pi/\omega_i$  are rationally incommensurable.

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Consider also the spatial periodic extension of this system

$$\sum_{j=1}^m \psi'_j = A(\varphi)\psi - \mu\psi, \quad (0.2_\mu)$$

where  $\psi : \mathbb{R}^m \rightarrow \mathbb{C}^n$  is an unknown vector function. Remark that if  $\psi$  is continuous and  $\omega_j$ -periodic in  $\varphi_j$  ( $j = 1, \dots, m$ ), then the conditionally periodic vector  $x(t) = \psi(et)$  solves system (0.1 $_\mu$ ).

The idea of the periodic extension of a conditionally periodic function goes back to P. Bohl [2], who was the founder of the theory of conditionally periodic functions and who proved that each continuous conditionally periodic function has a unique periodic extension.

If  $m = 1$ , then there exists a non-empty set  $M \subset \mathbb{C}$  such that for each  $\mu \in M$  system (0.1 $_\mu$ ) has a periodic solution.

We assume that  $m > 1$ . The problem is whether system (0.1 $_\mu$ ) has a conditionally periodic solution for some  $\mu \in \mathbb{C}$  (or system (0.2 $_\mu$ ) has a periodic one). This is well-known to be falls in general, even for  $n = 1$ . In this case,  $x(t) = c \exp \int_0^t (a(t) - \mu) dt$

is a solution of system (0.1 $_\mu$ ) with  $x(0) = c$ , and  $\int_0^t (a(t) - \mu) dt$  may not be conditionally periodic even though  $\mu$  is the mean value of  $a$ .

The aforementioned problem is related to that of the existence of almost periodic solutions of a homogeneous system [1, 3, 12, 11]. In these papers, some conditions have been given which ensure that a bounded solution of the homogeneous almost periodic system itself is Bohr almost periodic [1, 3, 12] or Besicovitch almost periodic [11].

Our approach is completely different.

Firstly, we assume nothing, but that the matrix  $A$  is sufficiently smooth. We prove that there exists a non-empty set  $M \subset \mathbb{C}$  such that, for any  $\mu \in M$ , there exists a periodic distribution  $\psi$  satisfying (0.2 $_\mu$ ). In a sequel to the present paper, we will apply this fact to prove that, for any  $\mu \in M$ , there exists a conditionally periodic distribution satisfying (0.1 $_\mu$ ).

Secondly, we consider a conditionally periodic system. This allows us to reduce the problem to the study of difference equation (0.6). This method is unlike any attempts to solve this problem that we are aware of.

Note that we used an inhomogeneous equation associated with (0.6) to prove an analogue of the Massera theorem in [10]. Namely, it was proved that if an inhomogeneous conditionally periodic system has a bounded solution, then almost every system in its H-class has a Besicovitch conditionally periodic bounded solution. The proof was based on the Schauder-Tikhonov fixed point theorem. Unfortunately, we were unable to apply this theorem in the case of a homogeneous system.

Thirdly, since in the general case system (0.2 $_\mu$ ) does not have a continuous periodic solution, we are looking for a solution in the space of periodic distributions, where apparently no one has looked for it yet.

**0.2.** We now present some results in [8] (see also [9]), which we are going to use. Since this paper is hardly available, we prove these results (Lemma 0.1) and Lemma 0.2 at the end of the paper.

Consider the system of integral equations

$$x(\varphi) = \int_0^{\varphi_1 - \varphi_{10}} A(\varphi - e\xi)x(\varphi - e\xi) d\xi + x_0(\hat{\varphi} - \hat{e}(\varphi_1 - \varphi_{10})), \quad (0.3)$$

where we use the "hat" operator to remove the first coordinate of the vector. Thereby,  $\hat{\varphi} = (\varphi_2, \dots, \varphi_m)$  and  $\hat{e} = (1, \dots, 1) \in \mathbb{R}^{m-1}$ . For each continuous function  $x^0: \mathbb{R}^{m-1} \rightarrow \mathbb{R}^n$ , this system has a unique continuous solution  $x = x(\varphi; \varphi_{10}, x^0)$ . This solution is  $\omega_k$ -periodic in  $\varphi_k$  if so is  $x^0$  ( $k = 2, \dots, m$ ). The vector  $x = x(et; \varphi_{10}, x^0)$  is a solution of system (0.1<sub>0</sub>) with  $x(e\varphi_{10}; \varphi_{10}, x^0) = x^0(\hat{e}\varphi_{10})$ .

Consider the matrix equation associated with (0.3)

$$X(\varphi) = \int_0^{\varphi_1 - \varphi_{10}} A(\varphi - e\xi)X(\varphi - e\xi) d\xi + E, \quad (0.4)$$

where  $E$  is the identity matrix. By  $X(\varphi; \varphi_{10})$  we denote the solution of this equation and  $X_0(\varphi) = X(\varphi; 0)$ .

**Lemma 0.1** . *Let  $A$  be a continuous  $\omega_j$ -periodic in  $\varphi_j$  ( $j=1, \dots, m$ ) matrix function. Then matrix equation (0.4) has a unique continuous solution  $X$ , and the following properties are true.*

(a) *The matrix  $X(\varphi; \varphi_{10})$  is non-singular for all  $\varphi \in \mathbb{R}^m$  and  $\varphi_{10} \in \mathbb{R}$ , and it is  $\omega_j$ -periodic in  $\varphi_j$  ( $j=2, \dots, m$ ).*

(b) *The solution of system (0.3) can be represented in the form*

$$x(\varphi; \varphi_{10}, x^0) = X(\varphi; \varphi_{10})x^0(\hat{\varphi} - \hat{e}(\varphi_1 - \varphi_{10})).$$

(c)  *$X(\varphi_1 + \omega_1, \hat{\varphi}; \varphi_{10}) = X(\varphi; \varphi_{10})X(\varphi_{10} + \omega_1, \hat{\varphi} - \hat{e}(\varphi_1 - \varphi_{10}); \varphi_{10})$ ; in particular,  $X_0(\varphi_1 + \omega_1, \hat{\varphi}) = X_0(\varphi)X_0(\omega_1, \hat{\varphi} - \hat{e}\varphi_1)$  [here the vector  $\varphi$  has the form  $(\varphi_1, \hat{\varphi})$ ].*

(d) *The matrix  $X_0(et)$  is the normalized fundamental matrix of system (0.1<sub>0</sub>).*

**Lemma 0.2.** *Let the matrix  $A$  be  $r$ -times continuously differentiable on  $\mathbb{R}^m$ ; then so is the matrix  $X_0$ .*

The matrix  $X_0$  is a solution of a differential equation, which we are going to get now. Put  $\varphi_1 - \xi = \zeta$  in (0.4). Then

$$X_0(\varphi) = \int_{\varphi_{10}}^{\varphi_1} A(\zeta, \hat{\varphi} + \hat{e}(\zeta - \varphi_{10}))X_0(\zeta, \hat{\varphi} + \hat{e}(\zeta - \varphi_{10})) d\zeta + E.$$

Let the matrix  $A$  be continuously differentiable; then so is  $X_0$ . Differentiating both sides of the above equation w.r.t.  $\varphi_j$  and summing w.r.t.  $j$  from 1 to  $m$ , we obtain

$$\sum_{j=1}^m (X_0)'_j = A(\varphi)X_0. \quad (0.5)$$

The key role in our research is played by the system

$$X_0(\omega_1, \hat{\varphi})L(\hat{\varphi} - \hat{e}\omega_1) = \lambda L(\hat{\varphi}). \quad (0.6)$$

Suppose that  $L: \mathbb{R}^{m-1} \rightarrow \mathbb{C}^n$  is a continuous  $\omega_j$ -periodic in  $\varphi_j$  ( $j = 2, \dots, m$ ) vector function which satisfies (0.6) for some  $\lambda \in \mathbb{C}$ ,  $\lambda \neq 0$ , and let  $\mu = \frac{1}{\omega_1} \ln \lambda$ . We claim that

$$\psi = X_0(\varphi)L(\hat{\varphi} - \hat{e}\varphi_1) \exp(-\mu\varphi_1)$$

is periodic,  $\psi(et)$  is the conditionally periodic solution of (0.1 <sub>$\mu$</sub> ), and if  $L$  is differentiable, then  $\psi$  satisfies (0.2 <sub>$\mu$</sub> ). Indeed,  $\psi$  is  $\omega_j$ -periodic in  $\varphi_j$  ( $j=2, \dots, m$ ) since  $X$

and  $L$  are so. Let us prove that it is periodic in  $\varphi_1$ . By item (c) of Lemma 0.1, we have

$$\begin{aligned} \psi(\varphi_1 + \omega_1, \hat{\varphi}) &= X_0(\varphi_1 + \omega_1, \hat{\varphi})L(\hat{\varphi} - \hat{e}(\varphi_1 + \omega_1))e^{-\mu\omega_1}e^{-\mu\varphi_1} \\ &= X_0(\varphi)X_0(\omega_1, \hat{\varphi} - \hat{e}\varphi_1)L(\hat{\varphi} - \hat{e}(\varphi_1 + \omega_1))\lambda^{-1}e^{-\mu\varphi_1} \\ &\stackrel{(0.6)}{=} X_0(\varphi)L(\hat{\varphi} - \hat{e}\varphi_1)\lambda\lambda^{-1}e^{-\mu\varphi_1} = \psi(\varphi). \end{aligned} \quad (0.7)$$

In view of item (d) of Lemma 0.1, it is clear that  $\psi(et) = X_0(et)L(\hat{0})e^{-\mu t}$  is the solution of (0.1 $_{\mu}$ ). That  $\psi$  solves (0.2 $_{\mu}$ ) one can check by direct calculation using (0.5) and the relation  $\sum_{j=1}^m (L(\hat{\varphi} - \hat{e}\varphi_1))'_j = 0$ .

In the first section of this paper, we present the basic facts about periodic distributions. After that we show that if there exists a periodic distribution  $L$  that solves (0.6) for some  $\lambda \neq 0$ , then  $\psi = X_0(\varphi)L(\hat{\varphi} - \hat{e}\varphi_1)\exp(-\mu\varphi_1)$  solves system (0.2 $_{\mu}$ ).

In the second section, we prove that there exists a non-empty set  $\Lambda \subset \mathbb{C}$  such that, for each  $\lambda \in \Lambda$ , the distribution  $L$  exists. And in the third section we prove Lemmas 0.1, 0.2.

## 1. PERIODIC DISTRIBUTIONS

The definition and properties of periodic distributions, which we use, can be found in the monographs [14, 15, 6]. We introduce the vector periodic distributions following [6] (see also [4, Ch.1]).

Let  $P_n^q(\omega)$  be the Banach space of  $\omega_j$ -periodic in  $\varphi_j$  ( $j = 1, \dots, m$ )  $q$ -times continuously differentiable functions  $y: \mathbb{R}^m \rightarrow \mathbb{C}^n$  with the norm  $\|y\|_{P_n^q(\omega)} = \max_{|r| \leq q} \max_{\varphi \in \mathbb{R}^m} \|D^r y(\varphi)\|$ , where  $\|\cdot\|$  is a norm on a finite-dimensional space,  $r = (r_1, \dots, r_m)$ ,  $r_j$  are non-negative integers,  $D^r y(\varphi) = \frac{\partial^{|r|} y(\varphi)}{\partial \varphi_1^{r_1} \dots \partial \varphi_m^{r_m}}$ , and  $|r| = r_1 + \dots + r_m$ .

Let  $P_{n_2}^q(\omega)$  be the Banach space of periodic  $q$ -times continuously differentiable  $n \times n$  matrices with the norm  $\|A\|_{P_{n_2}^q(\omega)} = \max_{|s| \leq n} \|a_s\|_{P_n^q(\omega)}$ , where  $a_s \in P_n^q(\omega)$  ( $s = 1, \dots, n$ ) are columns of  $A$ .

Denote by  $P_n^q(\omega)$  the space of linear continuous maps  $x: P_n^q(\omega) \rightarrow \mathbb{C}^n$ , where  $x = (x_1, \dots, x_n)^T$ ,  $x^T$  is the transpose of  $x$ , and  $x_k$  are linear continuous functionals on  $P_n^q(\omega)$ .

Every  $x \in P_n^q(\omega)$  determines the linear continuous functional on  $P_n^q(\omega)$  by the rule  $\langle x, y \rangle_{\omega} = \sum_{k=1}^n \langle x_k, y_k \rangle_{\omega}$ , where  $y = (y_1, \dots, y_n)^T \in P_n^q(\omega)$  and  $\langle x_k, y_k \rangle_{\omega}$  is the value of  $x_k$  at the point  $y_k \in P_n^q(\omega)$ .

The space  $P_n^q(\omega)$ , endowed with the norm  $\|x\|_{P_n^q(\omega)} = \sup_{\|y\|_{P_n^q(\omega)}=1} |\langle x, y \rangle_{\omega}|$ , is the Banach space, and it is isomorphic to the dual space of  $P_n^q(\omega)$  [6, p.267].

Consider the countably normed space  $P_n(\omega) = \bigcap_{q=0}^{\infty} P_n^q(\omega)$  and its dual  $P'_n(\omega) = \bigcup_{q=0}^{\infty} P_n^q(\omega)$ . By definition, a sequence  $\{y^k\}$  in  $P_n(\omega)$  converges to  $y \in P_n(\omega)$  if  $\|y^k - y\|_{P_n^q(\omega)} \rightarrow 0$  for every non-negative integer  $q$ , and  $\{x^k\}$  in  $P'_n(\omega)$  converges weakly to  $x \in P'_n(\omega)$  if  $\langle x^k - x, y \rangle_{\omega} \rightarrow 0$  for every  $y \in P_n(\omega)$  as  $k \rightarrow \infty$ . The latter is equivalent to the fact that  $x^k \rightarrow x$  weakly in some  $P_n^q(\omega)$  [4, Ch.1].

The space  $P'_1(\omega)$  is isomorphic to the space of the Schwartz periodic distributions [6, 14]. That is why  $x \in P'_1(\omega)$  is called an  $\omega$ -periodic distribution, and therefore  $x \in P'_n(\omega)$  we call an  $\omega$ -periodic vector distribution [15, 6]. Note that the term  $\omega$ -periodic is used for brevity. In fact,  $x \in P'_n(\omega)$  is  $\omega_j$ -periodic in  $\varphi_j$  ( $j = 1, \dots, m$ ), i.e.,

$$x(\varphi_1, \dots, \varphi_{j-1}, \varphi_j + \omega_j, \varphi_{j+1}, \dots, \varphi_m) = x(\varphi).$$

Indeed, by the definitions of equality and translation (see below on this page), we have

$$\begin{aligned} & \langle x(\varphi_1, \dots, \varphi_{j-1}, \varphi_j + \omega_j, \varphi_{j+1}, \dots, \varphi_m), y(\varphi) \rangle_\omega \\ &= \langle x(\varphi), y(\varphi_1, \dots, \varphi_{j-1}, \varphi_j - \omega_j, \varphi_{j+1}, \dots, \varphi_m) \rangle_\omega = \langle x(\varphi), y(\varphi) \rangle_\omega \end{aligned}$$

for any  $y \in P_n(\omega)$ .

We are going to mainly deal with the spaces of vector distributions  $P_n^q(\omega)$  and spaces of test functions  $P_n^q(\omega)$ . Suppose  $x, z \in P_n^q(\omega)$ . Let us remember the definitions of

$$\begin{aligned} \text{equality} &: x = z \Leftrightarrow \langle x, y \rangle_\omega = \langle z, y \rangle_\omega, \quad \forall y \in P_n^q(\omega); \\ \text{derivative} &: \langle x'_j, y \rangle_\omega = -\langle x, y'_j \rangle_\omega, \quad \forall y \in P_n^{q+1}(\omega); \\ \text{multiplication by matrix } A \in P_n^q(\omega) &: \langle Ax, y \rangle_\omega = \langle x, A^T y \rangle_\omega, \quad \forall y \in P_n^q(\omega); \\ \text{translation by } \tau &: \langle x(\varphi - \tau), y(\varphi) \rangle_\omega = \langle x(\varphi), y(\varphi + \tau) \rangle_\omega, \quad \forall y \in P_n^q(\omega), \\ & \tau \in \mathbb{R}^m. \end{aligned}$$

It was proved in the monographs [14, p.225], [15, p.130] that every  $x \in P'_n(\omega)$  has a unique Fourier-series expansion

$$x(\varphi) = \sum_{k \in \mathbb{Z}^m} c_k \exp(i(k\beta\varphi)), \quad (1.1)$$

where

$$\begin{aligned} c_k &= (\langle x_1(\varphi), \exp(-i(k\beta\varphi)) \rangle_\omega, \dots, \langle x_n(\varphi), \exp(-i(k\beta\varphi)) \rangle_\omega)^T / (\omega_1 \dots \omega_m), \\ k &= (k_1, \dots, k_m) \in \mathbb{Z}^m, \beta = (\beta_1, \dots, \beta_m), \beta_r = 2\pi/\omega_r, (k\beta\varphi) = \sum_{j=1}^m k_j \beta_j \varphi_j. \end{aligned}$$

Besides, there exist  $K > 0$  and  $p \in \mathbb{N}$  such that

$$\|c_k\| \leq K \|k\|^p, \quad k \in \mathbb{Z}^m. \quad (1.2)$$

Inversely, if there exist  $K > 0$  and  $p \in \mathbb{N}$  such that, for any  $k \in \mathbb{Z}^m$ , inequality (1.2) holds, then series (1.1) converges weakly and  $x \in P'_n(\omega)$  [6, pp.265,266], [14, p.225], [15, p.130].

It was shown in the previous section that if (0.6) has a continuous periodic solution  $L$ , then  $\psi(\varphi) = X_0(\varphi)L(\hat{\varphi} - \hat{e}\varphi_1) \exp(-\mu\varphi_1)$  is continuous and periodic. Now suppose that  $L \in P_n^r(\hat{\omega})$  and  $X_0 \in P_n^r(\omega)$  (for some non-negative integer  $r$ ); then  $\psi \in P_n^r(\hat{\omega})$  for any  $\varphi_1 \in \mathbb{R}$ . Likewise (see (0.7)), it can be proved that  $\psi$  is  $\omega_1$ -periodic in  $\varphi_1$ . That is why we are going to regard  $\psi$  as the distribution given by  $\langle \psi, y \rangle_\omega = \int_0^{\omega_1} \langle \psi, y \rangle_{\hat{\omega}} d\varphi_1$ ,  $y \in P_n^r(\omega)$ . Let us prove that  $\psi \in P_n^r(\omega)$ .

In this proof we use a standard fact in calculus : Let  $y : [\alpha, \beta] \times K \rightarrow \mathbb{C}^n$  be uniformly continuous for given  $\alpha, \beta \in \mathbb{R}$  and  $K \subset \mathbb{R}^{m-1}$ , let  $\{\varphi_{1k}\} \subset [\alpha, \beta]$ ; then  $\varphi_{1k} \rightarrow \varphi_{10}$  implies  $y(\varphi_{1k}, \hat{\varphi}) \rightarrow y(\varphi_{10}, \hat{\varphi})$  uniformly for  $\hat{\varphi} \in K$  as  $k \rightarrow \infty$ .

**Lemma 1.1.** Let  $A \in P_n^r(\omega)$ ,  $L \in P_n^r(\hat{\omega})$ , and  $r \geq 0$ ; then  $\psi(\varphi) = X_0(\varphi)L(\hat{\varphi} - \hat{e}\varphi_1) \exp(-\mu\varphi_1) \in P_n^r(\hat{\omega})$  for any  $\varphi_1 \in \mathbb{R}$  and the function  $g(\varphi_1) = \langle \psi, y \rangle_{\hat{\omega}}$  is continuous w.r.t.  $\varphi_1 \in [0, \omega_1]$  for every  $y \in P_n^r(\hat{\omega})$ .

*Proof.* By Lemma 0.2, it follows that  $X_0 \in P_{n^2}^r(\omega)$ . Hence,  $\psi \in P_n^r(\hat{\omega})$  for each  $\varphi_1 \in \mathbb{R}$ . Put  $X_{0\mu}(\varphi) = X_0(\varphi) \exp(-\mu\varphi_1)$ . Then  $\psi(\varphi) = X_{0\mu}(\varphi)L(\hat{\varphi} - \hat{e}\varphi_1)$ , and  $g$  can be written as  $g(\varphi_1) = \langle L(\hat{\varphi}), X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)y(\hat{\varphi} + \hat{e}\varphi_1) \rangle_{\hat{\omega}}$ . The vector  $v(\varphi) = X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)y(\hat{\varphi} + \hat{e}\varphi_1)$  and its partial derivatives of  $|j|$ th order ( $|j| = 1, \dots, r$ ) are uniformly continuous on  $[0, \omega_1] \times \mathbb{R}^{m-1}$ . Therefore, if  $[0, \omega_1] \ni \varphi_{1k} \rightarrow \varphi_{10} \in [0, \omega_1]$  as  $k \rightarrow \infty$ , then  $v(\varphi_{1k}, \hat{\varphi})$  and  $D^j v(\varphi_{1k}, \hat{\varphi})$  tend uniformly w.r.t.  $\hat{\varphi} \in \mathbb{R}^{m-1}$  to  $v(\varphi_{10}, \hat{\varphi})$  and  $D^j v(\varphi_{10}, \hat{\varphi})$  respectively. From this, remembering that  $L$  is a continuous mapping, we conclude that  $g(\varphi_{1k}) \rightarrow g(\varphi_{10})$ . Hence,  $g$  is continuous.  $\square$

**Lemma 1.2.** *Let  $A \in P_{n^2}^r(\omega)$ ,  $L \in P_n^r(\hat{\omega})$ , and  $r \geq 0$ ; then  $\psi \in P_n^r(\omega)$ .*

*Proof.* First, by using the fact that the mapping  $\langle \cdot, \cdot \rangle_{\hat{\omega}} : P_n^r(\hat{\omega}) \times P_n^r(\hat{\omega}) \rightarrow \mathbb{C}$  is bilinear and separately continuous, we prove that  $\langle \psi, y \rangle_{\hat{\omega}}$  is continuous in  $\varphi_1 \in [0, \omega_1]$  if  $y \in P_n^r(\hat{\omega})$ .

It follows from Lemma 1.1 that the function  $\psi : [0, \omega_1] \rightarrow P_n^r(\hat{\omega})$  is continuous, i.e.,  $[0, \omega_1] \ni \varphi_{1k} \rightarrow \varphi_{10}$  implies

$$\langle \psi(\varphi_{1k}, \cdot), z \rangle_{\hat{\omega}} \rightarrow \langle \psi(\varphi_{10}, \cdot), z \rangle_{\hat{\omega}} \quad (1.3)$$

for every  $z \in P_n^r(\hat{\omega})$ .

Besides, if  $y \in P_n^r(\hat{\omega})$ , then  $\|y(\varphi_{1k}, \hat{\varphi}) - y(\varphi_{10}, \hat{\varphi})\|_{P_n^r(\hat{\omega})} \rightarrow 0$  since the derivatives  $D^j y(\varphi)$ ,  $0 \leq |j| \leq r$  are uniformly continuous on  $\mathbb{R}^m$ , and hence

$$\langle x, y(\varphi_{1k}, \cdot) \rangle_{\hat{\omega}} \rightarrow \langle x, y(\varphi_{10}, \cdot) \rangle_{\hat{\omega}} \quad (1.4)$$

for each  $x \in P_n^r(\hat{\omega})$ .

Therefore, by the bilinear mapping continuity theorem [13, Th. 2.17], in view of relations (1.3) and (1.4), we get

$$\langle \psi(\varphi_{1k}, \cdot), y(\varphi_{1k}, \cdot) \rangle_{\hat{\omega}} \rightarrow \langle \psi(\varphi_{10}, \cdot), y(\varphi_{10}, \cdot) \rangle_{\hat{\omega}}, \quad y \in P_n^r(\hat{\omega}).$$

This proves that  $\langle \psi, y \rangle_{\hat{\omega}}$  is continuous and hence integrable w.r.t.  $\varphi_1 \in [0, \omega_1]$ .

To conclude the proof, we note that

$$\left| \int_0^{\omega_1} \langle \psi, y \rangle_{\hat{\omega}} d\varphi_1 \right| \leq \omega_1 \sup_{\varphi_1 \in [0, \omega_1]} |\langle \psi, y \rangle_{\hat{\omega}}| \leq \omega_1 K \sup_{\varphi_1 \in [0, \omega_1]} \|y\|_{P_n^r(\hat{\omega})} \leq \omega_1 K \|y\|_{P_n^r(\hat{\omega})}.$$

The existence of  $K = \sup_{\varphi_1 \in [0, \omega_1]} \|\psi\|_{P_n^r(\hat{\omega})}$  follows from the Principle of Uniform Boundedness. Indeed, due to Lemma 1.1,  $\langle \psi, y \rangle_{\hat{\omega}}$  is bounded in  $\varphi_1 \in [0, \omega_1]$  at each point  $y \in P_n^r(\hat{\omega})$ . Hence, the collection  $\{\langle \psi, \cdot \rangle_{\hat{\omega}} : \varphi_1 \in [0, \omega_1]\}$  of the continuous linear mappings from  $P_n^r(\hat{\omega})$  into  $\mathbb{C}$  is bounded. The inequality just obtained proves the lemma.  $\square$

*We say that  $\psi \in P_n^r(\omega)$  is a solution of system (0.2 $_{\mu}$ ) if*

$$\left\langle \sum_{i=1}^m \psi'_i, y \right\rangle_{\omega} = \langle A\psi - \mu\psi, y \rangle_{\omega} \quad (1.5)$$

for any  $y \in P_n^{r+1}(\omega)$ .

**Lemma 1.3.** *Let  $A \in P_{n^2}^r(\omega)$ ,  $L \in P_n^r(\hat{\omega})$  be a solution of (0.6) for some  $\lambda \neq 0$ ,  $r \geq 1$ , and  $\mu = \omega_1^{-1} \ln \lambda$ ; then the distribution  $\psi(\varphi) = X_{0\mu}(\varphi)L(\hat{\varphi} - \hat{e}\varphi_1) \in P_n^r(\omega)$  satisfies system (0.2 $_{\mu}$ ).*

*Proof.* It follows from Lemma 1.2 that  $\psi \in P_n^r(\omega)$ , and hence  $\psi'_j \in P_n^{r+1}(\omega)$ ,  $j = 1, \dots, m$ .

Let  $y \in P_n^{r+1}(\omega)$ . We are going to use the relations

$$\begin{aligned} & \int_0^{\omega_1} \langle L(\hat{\varphi} - \hat{e}\varphi_1), (X_{0\mu}^T(\varphi)A^T(\varphi) - \mu X_{0\mu}^T(\varphi))y(\varphi) \rangle_{\hat{\omega}} d\varphi_1 \\ &= \int_0^{\omega_1} \langle (A(\varphi)X_{0\mu}(\varphi) - \mu X_{0\mu}(\varphi))L(\hat{\varphi} - \hat{e}\varphi_1), y(\varphi) \rangle_{\hat{\omega}} d\varphi_1 \\ &= \langle A\psi - \mu\psi, y \rangle_{\omega} \end{aligned} \quad (1.6)$$

and

$$\begin{aligned} \partial X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)/\partial\varphi_1 &= \sum_{i=1}^m (X_{0\mu}^T)_i'(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \\ &= X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)A^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) - \mu X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1). \end{aligned} \quad (1.7)$$

The latter follows from (0.5).

So, remembering that  $y \in P_n^{r+1}(\omega)$ , we have

$$\begin{aligned} \langle \sum_{i=1}^m \psi'_i, y \rangle_{\omega} &= -\langle X_{0\mu}(\varphi)L(\hat{\varphi} - \hat{e}\varphi_1), \sum_{i=1}^m y'_i(\varphi) \rangle_{\omega} \\ &= -\int_0^{\omega_1} \langle L(\hat{\varphi} - \hat{e}\varphi_1), X_{0\mu}^T(\varphi) \sum_{i=1}^m y'_i(\varphi) \rangle_{\hat{\omega}} d\varphi_1 \\ &= -\int_0^{\omega_1} \langle L(\hat{\varphi}), X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)y'_1(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \rangle_{\hat{\omega}} d\varphi_1 \\ &\quad - \int_0^{\omega_1} \langle L(\hat{\varphi}), X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \sum_{i=2}^m y'_i(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \rangle_{\hat{\omega}} d\varphi_1. \end{aligned}$$

Denote the first summand at the right in the above relation by  $I_1$ , the second by  $I_2$ , and transform  $I_1$ .

$$\begin{aligned} I_1 &= -\int_0^{\omega_1} \langle L(\hat{\varphi}), X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)\partial y(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)/\partial\varphi_1 \rangle_{\hat{\omega}} d\varphi_1 \\ &\quad + \int_0^{\omega_1} \langle L(\hat{\varphi}), X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \sum_{i=2}^m y'_i(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \rangle_{\hat{\omega}} d\varphi_1 \\ &= \int_0^{\omega_1} \langle L(\hat{\varphi}), \partial X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)/\partial\varphi_1 y(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \rangle_{\hat{\omega}} d\varphi_1 \\ &\quad - \int_0^{\omega_1} \langle L(\hat{\varphi}), \partial(X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)y(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1))/\partial\varphi_1 \rangle_{\hat{\omega}} d\varphi_1 \\ &\quad + \int_0^{\omega_1} \langle L(\hat{\varphi}), X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \sum_{i=2}^m y'_i(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \rangle_{\hat{\omega}} d\varphi_1, \\ I_2 &= -\int_0^{\omega_1} \langle L(\hat{\varphi}), X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \sum_{i=2}^m y'_i(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \rangle_{\hat{\omega}} d\varphi_1. \end{aligned}$$

Hence,

$$\begin{aligned} I_1 + I_2 &= \int_0^{\omega_1} \langle L(\hat{\varphi}), \partial X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)/\partial\varphi_1 y(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \rangle_{\hat{\omega}} d\varphi_1 \\ &\quad - \int_0^{\omega_1} \langle L(\hat{\varphi}), \partial(X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)y(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1))/\partial\varphi_1 \rangle_{\hat{\omega}} d\varphi_1. \end{aligned}$$

We denote the first integral in the previous relation by  $J_1$  [and the second by  $J_2$ ] and transform it using (1.7):

$$\begin{aligned} J_1 &= \int_0^{\omega_1} \langle L(\hat{\varphi}), (X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)A^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \\ &\quad - \mu X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1))y(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \rangle_{\hat{\omega}} d\varphi_1 = \int_0^{\omega_1} \langle L(\hat{\varphi} - \hat{e}\varphi_1), (X_{0\mu}^T(\varphi)A^T(\varphi) \\ &\quad - \mu X_{0\mu}^T(\varphi))y(\varphi) \rangle_{\hat{\omega}} d\varphi_1 \stackrel{(1.6)}{=} \langle A\psi - \mu\psi, y \rangle_{\omega}. \end{aligned}$$

To transform  $J_2$ , we use differentiation of  $\langle \cdot, \cdot \rangle_{\hat{\omega}}$  w.r.t. parameter  $\varphi_1$  [14, p.105]:  $\langle L(\hat{\varphi}), \partial(X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1)y(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1))/\partial\varphi_1 \rangle_{\hat{\omega}}$

$$= \partial \langle L(\hat{\varphi}), X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) y(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \rangle_{\hat{\omega}} / \partial \varphi_1.$$

As a result, we get

$$\begin{aligned} J_2 &= \int_0^{\omega_1} \partial \langle L(\hat{\varphi}), X_{0\mu}^T(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) y(\varphi_1, \hat{\varphi} + \hat{e}\varphi_1) \rangle_{\hat{\omega}} / \partial \varphi_1 d\varphi_1 \\ &= \langle L(\hat{\varphi}), (X_{0\mu}^T(\omega_1, \hat{\varphi} + \hat{e}\omega_1) y(\omega_1, \hat{\varphi} + \hat{e}\omega_1) - X_{0\mu}^T(0, \hat{\varphi}) y(0, \hat{\varphi})) \rangle_{\hat{\omega}} \\ &= \langle X_{0\mu}(\omega_1, \hat{\varphi}) L(\hat{\varphi} - \hat{e}\omega_1) - X_{0\mu}(0, \hat{\varphi}) L(\hat{\varphi}), y(0, \hat{\varphi}) \rangle_{\hat{\omega}}. \end{aligned}$$

Remembering that  $L$  satisfies (0.6),  $X_{0\mu}(\omega_1, \hat{\varphi}) = X_0(\omega_1, \hat{\varphi}) \lambda^{-1}$ , and  $X_{0\mu}(0, \hat{\varphi}) = X_0(0, \hat{\varphi}) = E$ , we get  $J_2 = 0$ .

Summarizing all the above, we get (1.5).  $\square$

## 2. GENERALIZED SOLUTIONS OF SYSTEMS (0.6) AND (0.2 $_{\mu}$ )

Consider the system

$$X_0(\omega_1, \hat{\varphi}) L(\hat{\varphi} - \alpha_s) = \lambda L(\hat{\varphi}), \quad (2.1)$$

where  $\alpha_s = (p_{2s}\omega_2/q_{2s}, \dots, p_{ms}\omega_m/q_{ms})$ ,  $p_{js} \in \mathbb{Z}$ ,  $q_{js} \in \mathbb{N}$ . Due to the incommensurability of the frequencies  $\beta_i = 2\pi/\omega_i$ , we can choose  $p_{js}, q_{js}$  such that  $\alpha_s \rightarrow \hat{e}\omega_1$  as  $s \rightarrow \infty$ .

First, we want to prove that, for each  $s \in \mathbb{N}$ , there exists a distribution  $L_s$  which solves this system for some  $\lambda_s \in \mathbb{C}$ . Then we prove that the sequence  $\{L_s\}$  has a weak partial limit  $L$  which satisfies (0.6) for some  $\lambda \in \mathbb{C}$ .

**Lemma 2.1.** *Let  $A \in P_{n^2}^0(\omega)$ ; then, for any  $s \in \mathbb{N}$ , there exist a distribution  $L_s \in P_n^0(\hat{\omega})$  and a complex number  $\lambda_s \neq 0$  which satisfy (2.1).*

*Proof.* Let us endeavour to satisfy (2.1) by the distribution

$$L_s(\hat{\varphi}) = \sum_{j=0}^{\nu_s-1} f_{sj} \delta(\hat{\varphi} - j\alpha_s), \quad (2.2)$$

where  $\nu_s$  is the least common multiple of  $q_{js}$  ( $j = 2, \dots, m$ ),  $f_{sj}$  are constant column vectors, and  $\delta \in P_1^0(\hat{\omega})$  is the Dirac distribution:  $\langle f_{sj} \delta(\hat{\varphi} - \hat{\varphi}^0), y \rangle_{\hat{\omega}} = f_{sj}^T y(\hat{\varphi}^0)$ ,  $y \in P_n^0(\hat{\omega})$ .

Note that, in our case,  $\delta$  is a periodic functional since it is defined on the space of periodic functions.

Recall that  $L_s$  satisfies (2.1) if, for any  $y \in P_n^0(\hat{\omega})$ , the following relation holds

$$\langle X_0(\omega_1, \hat{\varphi}) L_s(\hat{\varphi} - \alpha_s), y \rangle_{\hat{\omega}} = \langle \lambda_s L_s(\hat{\varphi}), y \rangle_{\hat{\omega}}.$$

Upon substituting  $L_s$  into the left and right sides of this equation, we find

$$\begin{aligned} \langle X_0(\omega_1, \hat{\varphi}) L_s(\hat{\varphi} - \alpha_s), y(\hat{\varphi}) \rangle_{\hat{\omega}} &= \langle L_s(\hat{\varphi} - \alpha_s), (X_0(\omega_1, \hat{\varphi}))^T y(\hat{\varphi}) \rangle_{\hat{\omega}} \\ &= \langle L_s(\hat{\varphi}), (X_0(\omega_1, \hat{\varphi} + \alpha_s))^T y(\hat{\varphi} + \alpha_s) \rangle_{\hat{\omega}} \\ &= \sum_{j=0}^{\nu_s-1} \langle f_{sj} \delta(\hat{\varphi} - j\alpha_s), (X_0(\omega_1, \hat{\varphi} + \alpha_s))^T y(\hat{\varphi} + \alpha_s) \rangle_{\hat{\omega}} \\ &= \sum_{j=0}^{\nu_s-1} f_{sj}^T (X_0(\omega_1, (j+1)\alpha_s))^T y((j+1)\alpha_s) = \sum_{j=0}^{\nu_s-1} (X_0(\omega_1, (j+1)\alpha_s) f_{sj})^T y((j+1)\alpha_s) \end{aligned}$$

and

$$\langle \lambda_s L_s(\hat{\varphi}), y(\hat{\varphi}) \rangle_{\hat{\omega}} = \lambda_s \sum_{j=0}^{\nu_s-1} \langle f_{sj} \delta(\hat{\varphi} - j\alpha_s), y(\hat{\varphi}) \rangle_{\hat{\omega}} = \lambda_s \sum_{j=0}^{\nu_s-1} f_{sj}^T y(j\alpha_s)$$

Thus,

$$\sum_{j=0}^{\nu_s-1} (X_0(\omega_1, (j+1)\alpha_s) f_{sj})^T y((j+1)\alpha_s) = \lambda_s \sum_{j=0}^{\nu_s-1} f_{sj}^T y(j\alpha_s).$$

This relation holds if the vectors  $f_{sj}$  satisfy the system

$$\begin{cases} X_0(\omega_1, \alpha_s) f_{s0} & = & \lambda_s f_{s1} \\ X_0(\omega_1, 2\alpha_s) f_{s1} & = & \lambda_s f_{s2} \\ \dots & \dots & \dots \\ X_0(\omega_1, (\nu_s - 1)\alpha_s) f_{s\nu_s-2} & = & \lambda_s f_{s\nu_s-1} \\ X_0(\omega_1, \nu_s \alpha_s) f_{s\nu_s-1} & = & \lambda_s f_{s0}. \end{cases} \quad (2.3)$$

Indeed, let  $y \in P_n^0(\hat{\omega})$ . Then it follows from (2.3) that

$$\begin{cases} (X_0(\omega_1, \alpha_s) f_{s0})^T y(\alpha_s) & = & \lambda_s (f_{s1})^T y(\alpha_s) \\ (X_0(\omega_1, 2\alpha_s) f_{s1})^T y(2\alpha_s) & = & \lambda_s (f_{s2})^T y(2\alpha_s) \\ \dots & \dots & \dots \\ (X_0(\omega_1, (\nu_s - 1)\alpha_s) f_{s\nu_s-2})^T y((\nu_s - 1)\alpha_s) & = & \lambda_s (f_{s\nu_s-1})^T y((\nu_s - 1)\alpha_s) \\ (X_0(\omega_1, \nu_s \alpha_s) f_{s\nu_s-1})^T y(\nu_s \alpha_s) & = & \lambda_s (f_{s0})^T y(\nu_s \alpha_s). \end{cases}$$

Putting  $y(\nu_s \alpha_s) = y(\hat{0})$  in the right-hand side of the last equation and summing these equations, we obtain the desired relation.

It follows from (2.3) that

$$X_0(\omega_1, \nu_s \alpha_s) X_0(\omega_1, (\nu_s - 1)\alpha_s) \dots X_0(\omega_1, \alpha_s) f_{s0} = \lambda_s^{\nu_s} f_{s0}. \quad (2.4)$$

Consider some root  $G_s = (X_0(\omega_1, \nu_s \alpha_s) X_0(\omega_1, (\nu_s - 1)\alpha_s) \dots X_0(\omega_1, \alpha_s))^{\frac{1}{\nu_s}}$ , some eigenvalue  $\lambda_s$  of  $G_s$ , and the corresponding eigenvector  $f_{s0}$ ; then  $\lambda_s$  and  $f_{s0}$  satisfy (2.4). Substituting  $\lambda_s$  and  $f_{s0}$  into (2.3), we successively find the vectors  $f_{sk}, k = 1, \dots, \nu_s - 1$ . Hence, we get the distribution  $L_s$  which is a solution of (2.1). It can be seen from (2.2) that  $L_s \in P_n^0(\hat{\omega})$  since  $f_{sj} \delta(\hat{\varphi} - j\alpha_s) \in P_n^0(\hat{\omega})$ .  $\square$

**Lemma 2.2.** *Let  $A \in P_{n^2}^0(\omega)$  and let  $\lambda_s$  be an eigenvalue of  $G_s$ ,  $s \in \mathbb{N}$ ; then there exists a convergent subsequence  $\{\lambda_{s_k}\}$  of the sequence  $\{\lambda_s\}$  with nonzero limit.*

*Proof.* The matrix function  $X_0(\omega_1, \cdot)$  is non-singular, continuous, and  $\hat{\omega}$ -periodic in  $\hat{\varphi} \in \mathbb{R}^{m-1}$ . Hence, there exist  $\alpha, \beta > 0$  such that for any  $x \in \mathbb{R}^n$  and  $\hat{\varphi} \in \mathbb{R}^{m-1}$  we have  $\alpha \|x\| \leq \|X_0(\omega_1, \hat{\varphi})x\| \leq \beta \|x\|$ . From these inequalities we get  $\|G_s^{\nu_s}\| \leq \beta^{\nu_s}$  and  $\|G_s^{-\nu_s}\| \leq \alpha^{-\nu_s}$  (the matrix norm induced by the vector norm  $\|\cdot\|$  is also denoted by  $\|\cdot\|$ ). Since  $\lambda_s^{\nu_s}$  and  $\lambda_s^{-\nu_s}$  are eigenvalues of the matrices  $G_s^{\nu_s}$  and  $G_s^{-\nu_s}$  respectively, it follows that  $|\lambda_s^{\nu_s}| \leq \beta^{\nu_s}$  and  $|\lambda_s^{-\nu_s}| \leq \alpha^{-\nu_s}$ , and hence  $\alpha \leq |\lambda_s| \leq \beta$ ,  $s \in \mathbb{N}$ . On the strength of that there exists a partial limit  $\lambda$  of  $\{\lambda_s\}$  such that  $\alpha \leq |\lambda| \leq \beta$ . Hence, the desired subsequence exists.  $\square$

Now we want to show that there exist sequences  $\{\lambda_s\}$  and  $\{L_s\}$  such that  $\{L_s\}$  has a weak limit  $L$  which is a solution of (0.6) with  $\lambda = \lim \lambda_s$ .

Consider the Fourier-series of  $L_s$ :

$$L_s(\hat{\varphi}) = \sum_{\hat{k} \in \mathbb{Z}^{m-1}} t_{s\hat{k}} \exp(i(\hat{k}\hat{\beta}\hat{\varphi})),$$

where  $t_{s\hat{k}} = (\omega_2 \dots \omega_m)^{-1} \sum_{j=0}^{\nu_s-1} f_{sj} \exp(-ij(\hat{k}\hat{\beta}\alpha_s))$  and  $(\hat{k}\hat{\beta}\alpha_s) = \sum_{r=2}^m k_r \beta_r p_{sr} \omega_r / q_{sr}$ .

**Lemma 2.3.** *For each  $s \in \mathbb{N}$ , the mapping  $\hat{k} \rightarrow t_{s\hat{k}}$  is  $\nu_s$ -periodic w.r.t.  $k_r$  ( $r = 2, \dots, m$ ).*

*Proof.* Recall that  $\hat{k} = (k_2, \dots, k_m)$ ,  $\beta_r = 2\pi/\omega_r$ ,  $\nu_s$  is the least common multiple of  $q_{rs}$ , and  $\alpha_s = (p_{2s}\omega_2/q_{2s}, \dots, p_{ms}\omega_m/q_{ms})$ . Since  $\nu_s/q_{rs} \in \mathbb{Z}$  ( $r = 2, \dots, m$ ), we have

$$\begin{aligned} t_{s(k_2, \dots, k_r + \nu_s, \dots, k_m)} &= \sum_{j=0}^{\nu_k-1} f_{sj} \exp(-ij(\hat{k}\hat{\beta}\alpha_s + \nu_s(2\pi/\omega_r)p_{rs}\omega_r/q_{rs})) \\ &= \sum_{j=0}^{\nu_k-1} f_{sj} \exp(-ij(\hat{k}\hat{\beta}\alpha_s)) = t_{s\hat{k}}. \end{aligned}$$

□

**Lemma 2.4.** *For any  $\hat{j} \in \mathbb{Z}^{m-1}$ , in addition to  $L_s$  and  $\lambda_s$ , the pair  $L_s^{\hat{j}}(\hat{\varphi}) = \sum_{\hat{k} \in \mathbb{Z}^{m-1}} t_{s\hat{k}-\hat{j}} \exp(i(\hat{k}\hat{\beta}\hat{\varphi}))$  and  $\lambda_s^{\hat{j}} = \lambda_s \exp(-i(\hat{j}\hat{\beta}\alpha_s))$  also satisfies the system (2.1).*

*Proof.* Making a change  $\hat{k} - \hat{j} = \hat{r}$  in the Fourier-series of  $L_s^{\hat{j}}$ , we obtain  $L_s^{\hat{j}} = L_s \exp(i(\hat{\beta}\hat{j}\hat{\varphi}))$ . Then putting  $L_s = L_s^{\hat{j}} \exp(-i(\hat{\beta}\hat{j}\hat{\varphi}))$  into (2.1), we conclude that the lemma is true. □

**Lemma 2.5.** *Let, for any  $\hat{k} \in \mathbb{Z}^{m-1}$ , there exists  $t_{\hat{k}} = \lim_{s \rightarrow \infty} t_{s\hat{k}}$ , and let there exists  $C > 0$  such that for all  $s \in \mathbb{N}$  and  $\hat{k} \in \mathbb{Z}^{m-1}$  the inequality  $\|t_{s\hat{k}}\| \leq C$  holds. Then  $L_s \rightarrow L = \sum_{\hat{k} \in \mathbb{Z}^{m-1}} t_{\hat{k}} \exp(i(\hat{k}\hat{\beta}\hat{\varphi}))$  and  $L_s(\hat{\varphi} - \alpha_s) \rightarrow L(\hat{\varphi} - e\omega_1)$  weakly in  $P_n^r(\hat{\omega})$  for  $r \geq [\frac{m-1}{2}] + 1$  ( $[t]$  stands for the integral part of  $t$ ).*

*Proof.* Let  $y \in P_n^r(\hat{\omega})$ ,  $y_{\hat{k}}$  be the Fourier constants of  $y$ , and  $r \geq [\frac{m-1}{2}] + 1$ ; then  $\sum_{\hat{k} \in \mathbb{Z}^{m-1}} \|y_{\hat{k}}\|$  converges [5]. We say that  $\langle L_s, y \rangle_{\hat{\omega}} = \sum_{\hat{k} \in \mathbb{Z}^{m-1}} t_{s\hat{k}}^T y_{-\hat{k}}$  and  $\langle L, y \rangle_{\hat{\omega}} = \sum_{\hat{k} \in \mathbb{Z}^{m-1}} t_{\hat{k}}^T y_{-\hat{k}}$ . The proofs of these relations are similar since the boundedness of  $\{t_{s\hat{k}}\}$  implies  $\|t_{\hat{k}}\| \leq C$  for  $\hat{k} \in \mathbb{Z}^{m-1}$ , so we prove the first one. It holds if  $y = y^h = \sum_{\hat{k}} y_{\hat{k}} \exp(i(\hat{k}\hat{\beta}\hat{\varphi}))$  is a trigonometrical polynomial [15, p.132]. Besides, the series  $\sum_{\hat{k} \in \mathbb{Z}^{m-1}} t_{s\hat{k}}^T y_{-\hat{k}}$  converges because  $|t_{s\hat{k}}^T y_{-\hat{k}}| \leq C \|y_{-\hat{k}}\|$ . Therefore, we can take the limit in  $\langle L_s, y^h \rangle_{\hat{\omega}} = \sum_{\hat{k}} t_{s\hat{k}}^T y_{-\hat{k}}$  as  $h \rightarrow \infty$  and get the desired relation.

To prove the weak convergence of  $\{L_s\}$  to  $L = \sum_{\hat{k} \in \mathbb{Z}^{m-1}} t_{\hat{k}} \exp(i(\hat{k}\hat{\beta}\hat{\varphi}))$ , we consider  $\langle L_s - L, y \rangle_{\hat{\omega}} = \sum_{\hat{k} \in \mathbb{Z}^{m-1}} (t_{s\hat{k}} - t_{\hat{k}})^T y_{-\hat{k}}$ . For given  $\varepsilon > 0$  we find  $M_1, M_2$  such that  $\sum_{\|\hat{k}\| > M_1} \|y_{\hat{k}}\| < \varepsilon/(4C)$  and  $\sum_{\|\hat{k}\| \leq M_1} \|t_{\hat{k}} - t_{ks}\| < \varepsilon/(2C_1)$  for  $s > M_2$ , where  $C_1 = \max\{\|y_{\hat{k}}\| : \|\hat{k}\| \leq M_1\}$ . Then

$$\left| \sum_{\hat{k} \in \mathbb{Z}^{m-1}} (t_{s\hat{k}} - t_{\hat{k}})^T y_{-\hat{k}} \right| < C_1 \sum_{\|\hat{k}\| \leq M_1} \|t_{\hat{k}} - t_{ks}\| + 2C \sum_{\|\hat{k}\| > M_1} \|y_{\hat{k}}\| < \varepsilon$$

for  $s > M_2$ . Hence,  $L_s \rightarrow L$  weakly as  $s \rightarrow \infty$ . By the same argument, we have

$$\begin{aligned} \langle L_s(\hat{\varphi} - \alpha_s) - L(\hat{\varphi} - e\omega_1), y \rangle_{\hat{\omega}} = \\ \sum_{\hat{k} \in \mathbb{Z}^{m-1}} (t_{s\hat{k}} \exp(-i(\hat{k}\hat{\beta}\alpha_s)) - t_{\hat{k}} \exp(-i(\hat{k}\hat{\beta}\omega_1)))^T y_{-\hat{k}} \rightarrow 0 \end{aligned}$$

as  $s \rightarrow \infty$ .

Owing to the weak\* sequential completeness of  $P_n^{r'}(\hat{\omega})$ , we obtain  $L \in P_n^{r'}(\hat{\omega})$  since  $L_s \in P_n^{r_0}(\hat{\omega}) \subset P_n^{r'}(\hat{\omega})$ .  $\square$

**Theorem 2.1.** *Let  $A \in P_n^{r_0}(\omega)$  and  $r_0 = [\frac{m-1}{2}] + 1$ ; then there exist a distribution  $L \in P_n^{r_0}(\hat{\omega})$  and  $\lambda \neq 0$  satisfying (0.6).*

*Proof.* There exists a sequence  $\{L_s\}$  such that

$$\|t_{s\hat{0}}\| = 1 \geq \|t_{s\hat{k}}\| \quad (2.5)$$

for  $\hat{k} \neq \hat{0}$  and  $s \in \mathbb{N}$ . Indeed, due to Lemma 2.3, for each  $s \in \mathbb{N}$ , there exists  $t_{s\hat{k}_s}$  such that  $\|t_{s\hat{k}_s}\| \geq \|t_{s\hat{k}}\|$ ,  $\hat{k}_s \neq \hat{k}$ . Owing to Lemma 2.4, the distribution  $L_s^{-\hat{k}_s} / \|t_{s\hat{k}_s}\| = \sum_{\hat{k} \in \mathbb{Z}^{m-1}} \tilde{t}_{s\hat{k}} \exp(i(\hat{k}\hat{\beta}\hat{\varphi}))$  satisfies (2.1) for  $\lambda = \lambda_s \exp(i(\hat{k}_s\hat{\beta}\alpha_s))$ ; then  $\tilde{t}_{s\hat{k}} = t_{s\hat{k}+\hat{k}_s} / \|t_{s\hat{k}_s}\|$  satisfy (2.5).

Let the Fourier constants of  $L_s$  satisfy (2.5). Taking a subsequence if necessary, we may assume, in view of Lemma 2.2, that  $\lambda_s \rightarrow \lambda \neq 0$ . It follows from (2.5) that for each  $\hat{k} \in \mathbb{Z}^{m-1}$  the sequence  $\{t_{s\hat{k}}\}$  is bounded. Hence, there exists a sequence  $\{s_p\}$  of positive integers such that  $\lim_{p \rightarrow \infty} t_{s_p \hat{k}} = t_{\hat{k}}$  exists and  $\|t_{\hat{k}}\| \leq 1$  for each  $\hat{k} \in \mathbb{Z}^{m-1}$ . By Lemma 2.5, we get  $L_{s_p} \rightarrow L$  weakly in  $P_n^{r_0}(\hat{\omega})$ . Besides, by Lemma 0.2,  $X_0(\omega_1, \cdot) \in P_n^{r_0}(\hat{\omega})$ . Therefore,  $X_0(\omega_1, \cdot)L_{s_p} \rightarrow X_0(\omega_1, \cdot)L$  weakly in  $P_n^{r_0}(\hat{\omega})$ . Then taking limit in (2.1), we get  $X_0(\omega_1, \hat{\varphi})L(\hat{\varphi} - \hat{e}\varphi_1) = \lambda L(\hat{\varphi})$ . Moreover,  $L \neq 0$  since  $t_{\hat{0}} \neq 0$ .  $\square$

Consider the set of sequences  $\{\lambda_s\}$ , where  $\lambda_s$  is an eigenvalue of  $G_s$  and denote by  $\Lambda$  the set of partial limits of these sequences.

**Theorem 2.2.** *Let  $\lambda \in \Lambda$ ,  $\mu = \omega_1^{-1} \ln \lambda$ , and  $A \in P_n^{r_0}(\omega)$ ; then there exists a periodic distribution  $\psi \in P_n^{r_0}(\omega)$  that satisfies (0.2 $_{\mu}$ ).*

*Proof.* If  $A \in P_n^{r_0}(\omega)$ , then, by Theorem 2.1, there exists  $L \in P_n^{r_0}(\hat{\omega})$  satisfying (0.6). Therefore, Theorem 2.2 follows from Lemma 1.3.  $\square$

### 3. PROOF OF LEMMAS 0.1 AND 0.2

#### Lemma 0.1.

*Proof.* System (0.5) has the unique continuous solution

$$\begin{aligned} X(\varphi; \varphi_{10}) = E + \int_0^{\varphi_1 - \varphi_{10}} A(\varphi - e\xi) d\xi \\ + \sum_{k=2}^{\infty} \int_0^{\varphi_1 - \varphi_{10}} \int_0^{\varphi_1 - \varphi_{10} - \xi_k} \dots \int_0^{\varphi_1 - \varphi_{10} - \xi_2 - \dots - \xi_k} A(\varphi - e\xi_k) A(\varphi - e(\xi_k + \xi_{k-1})) \dots \\ A\left(\varphi - e \sum_{i=1}^k \xi_i\right) d\xi_1 \dots d\xi_k, \end{aligned} \quad (3.1)$$

which one can get by the method of successive approximations. Let  $\alpha, \beta \in \mathbb{R}$  be arbitrary. Then this series converges uniformly w.r.t.  $\varphi_1 \in [\alpha, \beta]$ ,  $\hat{\varphi} \in \mathbb{R}^{m-1}$  because it has the majorant

$$\sum_{s=0}^{\infty} \|A\|_{P_{n_2}^0(\omega)}^s |\varphi_1 - \varphi_{10}|^s / s!.$$

This solution is  $\omega_j$ -periodic in  $\varphi_j$  ( $j = 2, \dots, m$ ) since so is the right part of (3.1). Besides,

$$\begin{aligned} X(\varphi + et; \varphi_{10}) &= \int_0^{\varphi_1 + t - \varphi_{10}} A(\varphi + e(t - \xi)) X(\varphi + e(t - \xi); \varphi_{10}) d\xi + E \\ &= [t - \xi = \zeta] = \int_{\varphi_{10} - \varphi_1}^t A(\varphi + e\zeta) X(\varphi + e\zeta; \varphi_{10}) d\zeta + E. \end{aligned}$$

Therefore,

$$dX(\varphi + et; \varphi_{10})/dt = A(\varphi + et)X(\varphi + et; \varphi_{10}) \quad (3.2)$$

and  $X(\varphi_{10}, \hat{\varphi}; \varphi_{10}) = E$ . Consequently, the matrix  $X(\varphi + et, \varphi_{10})$ , being a fundamental matrix of the system

$$x' = A(\varphi + et)x,$$

is non-singular for  $\varphi \in \mathbb{R}^m$  and  $\varphi_{10} \in \mathbb{R}$ . In particular,  $X_0(et)$  is the normalized fundamental matrix of system (0.1<sub>0</sub>).

The fact that the function  $x(\varphi; \varphi_{10}, x^0) = X(\varphi; \varphi_{10})x^0(\hat{\varphi} - \hat{e}(\varphi_1 - \varphi_{10}))$  is a solution of system (0.3) we prove by substituting it into this system. Taking into account that  $x(\varphi - e\xi; \varphi_{10}, x^0) = X(\varphi - e\xi; \varphi_{10})x^0(\hat{\varphi} - \hat{e}(\varphi_1 - \varphi_{10}))$ , we get

$$\begin{aligned} &X(\varphi; \varphi_{10})x^0(\hat{\varphi} - \hat{e}(\varphi_1 - \varphi_{10})) \\ &= \int_0^{\varphi_1 - \varphi_{10}} A(\varphi - e\xi)X(\varphi - e\xi; \varphi_{10})x^0(\hat{\varphi} - \hat{e}(\varphi_1 - \varphi_{10})) d\xi + x^0(\hat{\varphi} - \hat{e}(\varphi_1 - \varphi_{10})) \\ &= \left( \int_0^{\varphi_1 - \varphi_{10}} A(\varphi - e\xi)X(\varphi - e\xi; \varphi_{10}) d\xi + E \right) x^0(\hat{\varphi} - \hat{e}(\varphi_1 - \varphi_{10})). \end{aligned}$$

This is true since  $X(\varphi; \varphi_{10})$  satisfies (0.4).

To prove (c), note that  $X(t + \omega_1, \hat{\varphi} + \hat{e}t; \varphi_{10})$  solves matrix equation (3.2). Hence,

$$X(t + \omega_1, \hat{\varphi} + \hat{e}t; \varphi_{10}) = X(t, \hat{\varphi} + \hat{e}t; \varphi_{10})Q. \quad (3.3)$$

Putting  $t = \varphi_{10}$  in this relation, we get  $Q = X(\varphi_{10} + \omega_1, \hat{\varphi} + \hat{e}\varphi_{10}; \varphi_{10})$ . Then substituting  $\varphi_1$  for  $t$  and  $\hat{\psi}$  for  $\hat{\varphi} + \hat{e}\varphi_1$  in (3.3), we get  $X(\varphi_1 + \omega_1, \hat{\psi}; \varphi_{10}) = X(\varphi_1, \hat{\psi}; \varphi_{10})X(\varphi_{10} + \omega_1, \hat{\psi} + \hat{e}(\varphi_{10} - \varphi_1); \varphi_{10})$ .  $\square$

### Lemma 0.2.

*Proof.* Let the matrix  $A$  be  $r$ -times continuously differentiable on  $\mathbb{R}^m$ . Then the matrix  $X$ , being a solution of system (3.2), is  $r$ -times continuously differentiable by the theorem on differentiability of the solution w.r.t. parameter  $\varphi$  [7, p.126].  $\square$

It is noteworthy that if  $\lambda_0 \in \Lambda$  and  $\mu_0 = \omega_1^{-1} \ln \lambda_0$ , then some system in the hull of  $(0.1_{\mu_0})$  has a bounded solution. It follows from this that  $\mu_0$  belongs to the Sacker-Sell spectrum of this system and  $\lambda_0$  belongs to the spectrum of the monodromy operator of this system. Besides, system  $(0.1_{\mu_0})$  has a generalized conditionally periodic solution. But these will be the objects of another paper.

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