

On Frequencies of Small Oscillations of Some Dynamical Systems Associated with Root Systems ¹

A M PERELOMOV

*Departamento de Física, Facultad de Ciencias, Universidad de Oviedo, Oviedo, Spain
On leave of absence from Institute for Theoretical and Experimental Physics,
117259 Moscow, Russia
E-mail: perelomo@dftuz.unizar.es*

Received May 29, 2002; Accepted July 07, 2002

Abstract

In the paper by F Calogero and the author [*Commun. Math. Phys.* **59** (1978), 109–116] the formula for frequencies of small oscillations of the Sutherland system (A_l case) was found. In the present note the generalization of this formula for the case of arbitrary root system is given.

1 Introduction

In this note, we consider the classical Hamiltonian systems associated to the root systems, with the potential $v(q) = g^2 \sin^{-2} q$. Such systems were introduced in [18] as the generalization of the Calogero–Sutherland systems [3, 25].

It is known that these systems have the equilibrium configurations which are distinguished by many remarkable features (see papers [1, 2, 4, 5, 7, 8, 9, 13, 17, 19, 23] and books [6, 24]). In the simplest case (A_l case with the potential $v(q) = g^2 \sin^{-2} q$), the explicit expression for frequencies of small oscillations near equilibrium was found in the paper [7]. For the case of the potential $v(q) = q^2 + g^2 q^{-2}$, these frequencies are known for the case of arbitrary root system and they are proportional to the degrees of basic invariants of the Weyl group of the corresponding root system [23].

The main result of this note is the explicit formula for the frequencies of such oscillations for the trigonometric case. Namely, these frequencies are proportional to the coefficients $r_j(g)$ in the expansion of the sum of positive roots in the simple roots $\{\alpha_j\}$:

$$2\rho(g) = \sum_{\alpha \in R^+} g_\alpha \alpha = \sum_{j=1}^l r_j(g) \alpha_j. \quad (1)$$

This is the generalization of the old result by Calogero and author [7] (for numerical calculations of such type quantities see [9]).

Copyright © 2003 by A M Perelomov

¹math-ph/0205039

As a byproduct of the calculations at $g_\alpha = 1$, we discovered the identity for the root systems which we cannot find in the literature, namely,

$$\prod_{j=1}^l (d_j - 1)d_j = z \cdot \prod_{k=1}^l r_k. \quad (2)$$

Here $\{d_j\}$ are the degrees of the basic invariants of the root systems, and $z = z(G)$ is the dimension of the center of the simple compact simply-connected Lie group G corresponding to the root system R .

2 General description

The systems under consideration were introduced in [18] and they are described by the Hamiltonian (for more details, see [19] and [24])

$$H = \frac{1}{2}p^2 + U(q), \quad p^2 = (p, p) = \sum_{j=1}^l p_j^2, \quad (3)$$

where $p = (p_1, \dots, p_l)$, and $q = (q_1, \dots, q_l)$ are the momentum vector and the coordinate one in the l -dimensional vector space $V \sim \mathbb{R}^l$ with the standard scalar product (\cdot, \cdot) . The potential $U(q)$ is constructed by means of the certain system of vectors $R = \{\alpha\} = R^+ \cup R^-$ in V , so-called root system.

$$U = \sum_{\alpha \in R^+} g_\alpha^2 v(q_\alpha), \quad q_\alpha = (\alpha, q). \quad (4)$$

The constants g_α satisfy the condition $g_\alpha = g_\beta$ if $(\alpha, \alpha) = (\beta, \beta)$. Such systems are completely integrable for $v(q)$ of five types. Here we consider only the case $v(q) = \sin^{-2} q$.

Note that these systems are the generalization of the Calogero–Sutherland systems [3] and [25], for which $R^+ = \{e_i - e_j, i < j\}$ and $\{e_j\}, j = 1, \dots, l + 1$ is the standard basis in \mathbb{R}^{l+1} .

3 Root systems

We give here the basic definitions. For more details, see [12, 15] and [21]. Let V be the l -dimensional real vector space with a standard scalar product (\cdot, \cdot) , $(\alpha, \beta) = \sum \alpha_j \beta_j$, and let s_α be the reflection in the hyperplane through the origin orthogonal to the vector α

$$s_\alpha q = q - (q, \alpha^\vee) \alpha, \quad \alpha^\vee = \frac{2}{(\alpha, \alpha)} \alpha. \quad (5)$$

Consider a finite set of nonzero vectors $R = \{\alpha\}$ generating V and satisfying the following conditions:

1. For any $\alpha \in R$, the reflection s_α conserves R : $s_\alpha R = R$.
2. For all $\alpha, \beta \in R$, we have $(\alpha^\vee, \beta) \in \mathbb{Z}$.

The set $\{s_\alpha\}$ generates the finite group $W(R)$ – the Weyl group of R . The root system R is called *reduced system* if only vectors in R collinear to α are $\pm\alpha$. Let us choose the hyperplane which does not contain the root. Then we have $R = R^+ \cup R^-$, and R^+ is the set of positive roots. In R^+ there is the basis $\{\alpha_1, \dots, \alpha_l\}$ (the set of simple roots) such that $\alpha = \sum_j n_j \alpha_j$, $n_j \geq 0$ for any $\alpha \in R^+$. The root system R is called *irreducible system* if it can not be the union of two non-empty subsets R_1 and R_2 which are orthogonal each other.

Let $\{\alpha_1, \dots, \alpha_l\}$ be the set of simple roots in R , R^+ be the set of positive roots, and $\{\lambda_j\}$ be a dual basis or the weight basis: $(\lambda_j, \alpha_k) = \delta_{jk}$.

Let Q be the root lattice, and Q^+ be the cone of positive roots

$$Q = \left\{ \beta : \beta = \sum_{j=1}^l m_j \alpha_j, m_j \in \mathbb{Z} \right\}; \quad Q^+ = \left\{ \gamma : \gamma = \sum_{j=1}^l n_j \alpha_j, n_j \in \mathbb{N} \right\}. \quad (6)$$

Let P be the weight lattice, and P^+ be the cone of dominant weights

$$P = \left\{ \lambda : \lambda = \sum_{j=1}^l m_j \lambda_j, m_j \in \mathbb{Z} \right\}; \quad P^+ = \left\{ \mu : \mu = \sum_{j=1}^l n_j \lambda_j, n_j \in \mathbb{N} \right\}. \quad (7)$$

Following [15], we define a partial order on P as follows: $\lambda \geq \mu$ if and only if $\lambda - \mu \in Q^+$ (or $(\lambda, \lambda_j) \geq (\mu, \lambda_j)$ for all $j = 1, \dots, l$). The set of linear combinations over \mathbb{R} of the functions $f_\lambda(q) = \exp\{2i(\lambda, q)\}$, $\lambda \in P$, $q \in V$ may be considered as the group algebra A over \mathbb{R} of the free abelian group P . For any $\lambda \in P$, let us denote $e^\lambda \sim f_\lambda(q)$ as the corresponding element of A , so that $e^\lambda e^\mu = e^{\lambda+\mu}$, $(e^\lambda)^{-1} = e^{-\lambda}$, and $e^0 = 1$, the identity element of A . Then e^λ , $\lambda \in P$ form the \mathbb{R} -basis of A .

The Weyl group $W(R)$ acts on P and hence also on A : $s(e^\lambda) = e^{s\lambda}$ for $s \in W$ and $\lambda \in P$. We denote as A^W the subalgebra of W -invariant elements of A .

It is known that A^W is the algebra free generated by basic invariants of degrees d_1, \dots, d_l . We introduce also a g -deformed vector

$$\rho(g) = \frac{1}{2} \sum_{\alpha \in R^+} g_\alpha \alpha.$$

Let δ be the highest root, i.e. the positive root such that $\delta \geq \alpha$ for all $\alpha \in R^+$.

4 Results

Let us consider two classical systems characterized by the Hamiltonians

$$H_m = \frac{1}{2} p^2 + U_m(q), \quad m = 1, 2 \quad (8)$$

with

$$U_1(q) = - \sum_{\alpha \in R^+} g_\alpha \log |\sin(q_\alpha)|, \quad (9)$$

$$U_2(q) = \sum_{\alpha \in R^+} g_\alpha^2 \sin^{-2}(q_\alpha), \quad q_\alpha = (\alpha, q), \quad g_\alpha = g_\beta \quad \text{if } (\alpha, \alpha) = (\beta, \beta). \quad (10)$$

The configuration space of such system is the Weyl alcove

$$\{q \mid (q, \alpha_j) > 0, j = 1, \dots, l, (q, \delta) < \pi\}, \quad (11)$$

where $\{\alpha_j\}$ is the set of the simple roots, δ is the highest root, and as it well known the potential energies U_1 and U_2 have an isolated minimum at the point \bar{q} inside the alcove². Let us denote this minimum as $U_1^{(0)}$ and $U_2^{(0)}$, $U_m^{(0)} = U_m(\bar{q})$. Then near this point we have

$$U_m(q) \sim U_m^{(0)} + \frac{1}{2} a_{jk}^{(m)} \xi_j \xi_k, \quad \xi_j = q_j - \bar{q}_j. \quad (12)$$

The matrices $a^{(m)}$ are positive definite and as it is known [23],

$$a^{(2)} = c(a^{(1)})^2, \quad c = \text{const.} \quad (13)$$

So, we need to know just one of them. The frequencies of small oscillations $\omega_j^{(m)}$ near the equilibrium configuration are square roots of eigenvalues of these matrices and we have $\omega_j^{(2)} = c(\omega_j^{(1)})^2$. The eigenvalues of these matrices were known before only for A_l case (see [7]). Here we give the explicit expression for them for the general case.

Theorem. *Eigenvalues of the matrix $a^{(1)}$ are equal to the quantities $\{2r_j(g)\}$, $j = 1, \dots, l$, where $\{r_j(g)\}$ are the coefficients in the expansion*

$$2\rho(g) = \sum_{\alpha \in R^+} g_\alpha \alpha = \sum_{j=1}^l r_j(g) \alpha_j. \quad (14)$$

Proof. Note that the function $U_1(q)$ is equal to $-\log |\Psi_0^\kappa|$, where Ψ_0^κ is the solution of the Schrödinger equation [20]

$$\left(\frac{1}{2} \hat{p}^2 + U_2(q) \right) \Psi_0^\kappa = E_0(\kappa) \Psi_0^\kappa, \quad g_\alpha^2 = \kappa_\alpha (\kappa_\alpha - 1), \quad \hat{p}_j = -i \frac{\partial}{\partial q_j}, \quad (15)$$

$$\Psi_0^\kappa = \prod_{\alpha \in R^+} (\sin q_\alpha)^{\kappa_\alpha}. \quad (16)$$

The function $\Psi_0^\kappa(q)$ is positive inside the Weyl alcove and has a maximum at point $q = \bar{q}$. Let $\kappa_\alpha = s \tilde{\kappa}_\alpha$ and let us consider the limit as $s \rightarrow \infty$.

Then the function

$$\Phi_0^{\tilde{\kappa}}(\xi) = \lim_{s \rightarrow \infty} \frac{\Psi_0^\kappa(\bar{q} + \xi/\sqrt{s})}{\Psi_0^\kappa(\bar{q})}, \quad \kappa_\alpha = s \tilde{\kappa}_\alpha \quad (17)$$

takes the Gaussian form³

$$\Phi_0^{\tilde{\kappa}}(\xi) = \exp \left(-\frac{1}{2} a_{jk} \xi_j \xi_k \right). \quad (18)$$

²Let us note that the first system is the generalization of the so-called ‘‘Dyson system’’ [10, 11].

³In other words at the limit $\kappa_\alpha \rightarrow \infty$ ($s \rightarrow \infty$) our quantum system becomes the oscillatory one for which the correspondence between classical and quantum systems is well known. Note that at this limit wave functions go to oscillatory ones. For example, for the case of one degree of freedom we have

$$\lim_{s \rightarrow \infty} s^{(-n/2)} P_n^{(\alpha, \alpha)}(x/\sqrt{s}) = (2^n n!)^{-1} H_n(x),$$

where $P_n^{(\alpha, \beta)}(x)$ and $H_n(x)$ are Jacobi and Hermite polynomials, correspondingly. For the multidimensional case, analogous formulae give the multivariable Hermite polynomials.

From other side, at this limit the Schrödinger equation

$$\left(\frac{1}{2}\hat{p}^2 + U_2(q)\right)\Psi_{\mathbf{m}} = E_{\mathbf{m}}\Psi_{\mathbf{m}}, \quad \mathbf{m} = (m_1, \dots, m_l) \quad (19)$$

takes the form

$$\left(-\Delta_{\xi} + \frac{1}{2}\sum_{j,k=1}^l b_{j,k}\xi_j\xi_k\right)\Phi_{\mathbf{m}} = \tilde{E}_{\mathbf{m}}\Phi_{\mathbf{m}}, \quad (20)$$

where

$$b = a^2, \quad \tilde{E}_{\mathbf{m}} = \tilde{E}_0 + \sum_{j=1}^l \omega_j m_j, \quad (21)$$

and ω_j are the eigenvalues of the matrix a . Note that the spectrum of the quantum problem

$$H\Psi_{\mathbf{m}} = E_{\mathbf{m}}\Psi_{\mathbf{m}}$$

is given by the formula

$$E_{\mathbf{m}} = \sum_{i,j=1}^l (\lambda_i, \lambda_j) m_i m_j + 2 \sum_{j=1}^l (\lambda_j, \rho(\kappa)) m_j + E_0(\kappa). \quad (22)$$

At $s \rightarrow \infty$ we obtain

$$\tilde{E}_{\mathbf{m}} = \lim_{s \rightarrow \infty} (s^{-1} E_{\mathbf{m}}(\kappa)) = \tilde{E}_0 + 2 \sum_{j=1}^l (\lambda_j, \rho(\tilde{\kappa})) m_j. \quad (23)$$

Comparing (21) and (23), we obtain the main formula

$$(\omega_j^{(1)})^2 = 2r_j(\tilde{\kappa}) = 2(\lambda_j, \rho(\tilde{\kappa})). \quad (24)$$

So, the classical result is obtained from the quantum result as $s \rightarrow \infty$. ■

In conclusion, we give the explicit expression for the maximum value of the function $\Psi_0^{\kappa}(q)$.

This formula was given by I Macdonald as an conjecture [14] that was proved later by E Opdam [22]. For the simplest case ($\kappa_{\alpha} = 1$ for all α), it has the form

$$|\Psi_0^1(\bar{q})|^2 = \left\{ \prod_{\alpha \in R^+} (\sin \bar{q}_{\alpha}) \right\}^2 = \frac{|W|}{2^{|R|}} \prod_{j=1}^l \left(\frac{d_j}{d_j - 1} \right)^{d_j - 1}, \quad (25)$$

where $|W|$ is the order of W , and $|R|$ is the number of roots.

Acknowledgements

I am grateful to Prof. R Sasaki who raised the question on small oscillations and to the Physics Department of Oviedo University for the hospitality.

References

- [1] Ahmed S, Bruschi M, Calogero F, Olshanetsky M A and Perelomov A M, Properties of the Zeros of the Classical Polynomials and of Bessel Functions, *Nuovo Cim.* **49** (1979), 173–199.
- [2] Bordner A J, Manton N S and Sasaki R, Calogero–Moser Models V: Supersymmetry, and Quantum Lax Pairs, *Prog. Theor. Phys.* **103** (2000), 463–487; hep-th/9910033.
- [3] Calogero F, Solution of the One-Dimensional N -Body Problem with Quadratic and/or Inversely Quadratic Pair Potentials, *J. Math. Phys.* **12** (1971), 419–436.
- [4] Calogero F, On the Zeros of the Classical Polynomials, *Lett. Nuovo Cim.* **19** (1977), 505–508.
- [5] Calogero F, Equilibrium Configuration of the One-Dimensional n -Body Problem with Quadratic and Inversely Quadratic Pair Potentials, *Lett. Nuovo Cim.* **20** (1977), 251–253.
- [6] Calogero F, Classical Many-Body Problems in One-Two- and Three-Dimensional Space Amenable to Exact Treatments (Solvable and/or Linearizable), Springer-Verlag, 2001.
- [7] Calogero F and Perelomov A M, Properties of Certain Matrices Related to the Equilibrium Configuration of One-Dimensional Many-Body Problems with Pair Potentials $V_1 = -\log |\sin x|$ and $V_2 = 1/\sin^2 x$, *Commun. Math. Phys.* **59** (1978), 109–116.
- [8] Calogero F and Perelomov A M, Some Diophantine Relations Involving Circular Functions of Rational Angles, *Lin. Alg. Appl.* **25** (1979), 91–94.
- [9] Corrigan E and Sasaki R, Quantum VS Classical Integrability in Calogero–Moser Systems, 2002, hep-th/0204039.
- [10] Dyson F J, Statistical Theory of the Energy Levels of Complex Systems, I, II, III, *J. Math. Phys.* **3** (1962), 140–156, 157–165, 166–175.
- [11] Dyson F J, A Brownian Motion Model for the Eigenvalues of a Random Matrix, *J. Math. Phys.* **3** (1962), 1191–1198.
- [12] Humphreys J E, Introduction to Lie Algebras and Representation Theory, Springer, New York, 1972.
- [13] Kogan Ya I, Perelomov A M and Semenov G, Charge Distribution in Two-Dimensional Electrostatics, *Phys. Rev.* **B45**, Nr. 20 (1992), 12084–12087.
- [14] Macdonald I, Some Conjectures for Root Systems, *SIAM J. Math. Anal.* **13** (1982), 988–1007.
- [15] Macdonald I, Orthogonal Polynomials Associated with Root Systems, Preprint, 1987.
- [16] Macdonald I, Symmetric Functions and Hall Polynomials, Oxford Univ. Press, 1995.
- [17] Mikhailov A V, Olshanetsky M A and Perelomov A M, Two-Dimensional Generalized Toda Lattice, *Commun. Math. Phys.* **79** (1981), 473–488.
- [18] Olshanetsky M A and Perelomov A M, Completely Integrable Hamiltonian Systems Connected with Semisimple Lie Algebras, *Invent. Math.* **37** (1976), 93–108.
- [19] Olshanetsky M A and Perelomov A M, Classical Integrable Finite-Dimensional Systems Related to Lie Algebras, *Phys. Repts.* **71** (1981), 314–400.
- [20] Olshanetsky M A and Perelomov A M, Quantum Integrable Systems Related to Lie Algebras, *Phys. Repts.* **94** (1983), 313–404.

-
- [21] Onishchik A L and Vinberg E B, *Lie Groups and Algebraic Groups*, Springer-Verlag, Berlin–Heidelberg, 1990.
 - [22] Opdam E, Some Applications of Hypergeometric Shift Operators, *Invent. Math.* **98** (1989), 1–18.
 - [23] Perelomov A M, Equilibrium Configurations and Small Oscillations of Some Dynamical Systems, *Ann. Inst. H. Poincaré* **A28** (1978), 407–415.
 - [24] Perelomov A M, *Integrable Systems of Classical Mechanics and Lie Algebras. I*, Birkhauser, 1990.
 - [25] Sutherland B, Exact Results for a Quantum Many-Body Problem in One-Dimension. II, *Phys. Rev.* **A5** (1972), 1372–1376.