CIRP Journal of Manufacturing Science and Technology 11 (2015) 82–88

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Magnetic attraction forces between permanent magnet group arrays in a mobile magnetic clamp for pocket machining☆

A. Mahmud *, J.R.R. Mayer, L. Baron

Département de génie mécanique, Polytechnique Montréal, C.P. 6079, succ. Centre-ville, Montréal, Canada

ARTICLE INFO

Article history:
Available online 26 September 2015

Keywords:
Magnet array
Cylindrical permanent magnet
Magnetic axial force

ABSTRACT

A mobile magnetic clamp was recently tested for pocket milling on a fuselage panel. The magnetic clamps need to provide sufficient support force against the milling thrust force and sufficient drag force to overcome the frictional force. Triangular arrays of cylindrical permanent magnets are used. Axial magnetic attraction forces between magnet groups are calculated based on recently published formula at various axial heights and lateral displacements. A model is here proposed to estimate lateral magnetic attraction forces as a function of lateral displacement between two cylindrical permanent magnets. Experiments conducted using a dynamometer table to validate the measured axial and lateral magnetic forces strongly support the analytically predicted magnetic forces.

Introduction

This paper describes an analytical force model between two permanent magnet groups arranged in a triangular array fashion. The model is then used to assess whether the forces generated are sufficient to counteract both the milling forces and frictional forces affecting the mobile magnetic clamp. The magnetic clamp [1] main function is to hold a panel while pockets are machined on its surface. At the same time since it must slide over the panel, friction forces are generated. Axial magnetic attraction force between three closely located pairs of cylindrical magnets provides the support force to keep the panel in position. Lateral attraction force between the cylindrical permanent magnet pulls the slave part of the clamp over the panel to keep it close to the master part of the clamp. Axial and lateral magnetic force directions are shown in Fig. 1.

Vučković et al. [2] presented a semi-analytical approach for the determination of the magnetic levitation force between two laterally displaced cylindrical permanent magnets. Fictitious magnetization charges and the discretization technique were adopted for cylindrical magnets assuming similar magnetic material and uniform magnetization along their axes of symmetry (opposite direction).

Ravaud et al. [3] published an analytical expression to calculate the mutual inductance (axial force) between two axially magnetized cylindrical permanent magnets in air. Due to high computation time and complex valued results a simplified equation was later proposed by Robertson et al. [4].

Formulas have also been proposed by Agashe and Arnold [5] for the attraction forces between two uniformly magnetized cylindrical permanent magnets. Kelvin formula was employed to derive explicit analytical solutions for axial and lateral forces. Long and elaborated equations result for practical application based calculation.

All aforementioned paper considered face to face (aligned with no lateral displacement) interaction of a single pair of permanent cylindrical magnet but Vokoun et al. [6] used a Bessel function based attraction force equation to elaborate axial force for more than two cylindrical magnets with the special case of two groups magnet set each comprising four magnets. Later Vokoun et al. [7] generalized the attraction force equation for two infinite arrays of cylindrical magnets.

In the case of a mobile magnetic clamp the corresponding magnets of each group do not remain coaxial. Due to frictional forces the slave module lags behind the master module introducing a lateral displacement. It is necessary to estimate the axial force between master and slave triangular magnets groups considering this lateral displacement. In this paper Vokoun's Bessel function based equations are used for determining the axial magnetic force between triangular magnetic groups for different lateral and axial displacement. Additionally, a formulation is proposed, and

☆ This work was supported by the project "Machining of skin panels (Al or Al-Li)", CRIAQ MANU-412 – NSERC RDCPJ 411911 – 10).

* Corresponding author. Tel.: +1 4384011379.
E-mail addresses: apple.mahmud@polymtl.ca (A. Mahmud), rene.mayer@polymtl.ca (J.R.R. Mayer), luc.baron@polymtl.ca (L. Baron).

http://dx.doi.org/10.1016/j.cirpj.2015.08.005
1755-5817/© 2015 CIRP.

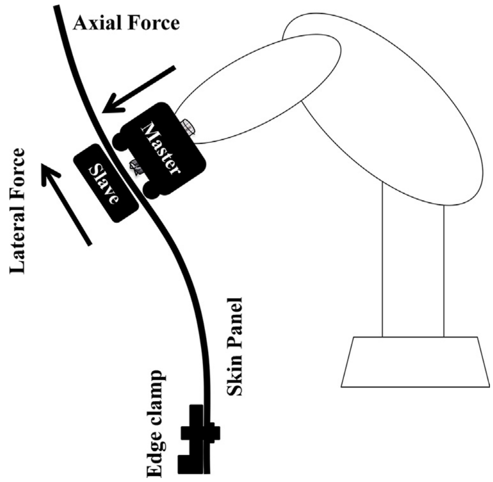

Fig. 1. Axial and lateral magnetic force direction in the mobile magnetic clamp.

experimentally validated, to explain the lateral magnetic force using Bessel function of the first kind.

Theoretical framework

The mobile magnetic clamp has three gripping sets forming, with the contact mechanisms, a kinematic contact system to avoid redundancy and contact ambiguity in planar gripping. Three permanent cylindrical magnets are used at each group to support the axial force generated by the milling operation. Each group has three magnets at the vertices of an equilateral triangle. These three groups of permanent magnets are located on a circumference 120 degrees apart completing the array (Fig. 2). Similar arrangements are adopted both in the master and slave array. A magnet in the master module array has an opposite magnet in the slave module array, forming a pair. The magnets of each pair are nominally coaxial.

The clamping contact point is at the centroid of each group where a ball transfer unit is attached (Fig. 3). A magnet attracts the opposite pole and repels the similar pole. Since these permanent magnets are axially magnetized the N-S-N-S orientation is used to get the highest possible attraction force as shown in Fig. 4.

Coaxial magnets located in the master and slave array have their own magnetic attraction forces between them (Fig. 4). However, the other two magnets of the same group have an

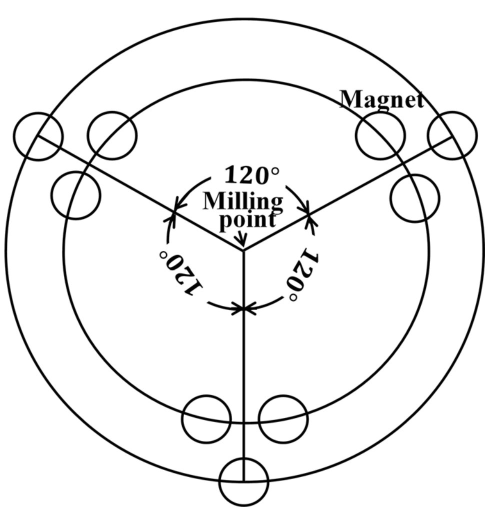

Fig. 2. Three magnets group (each group comprised of three individual magnets) located in the master array and slave array.

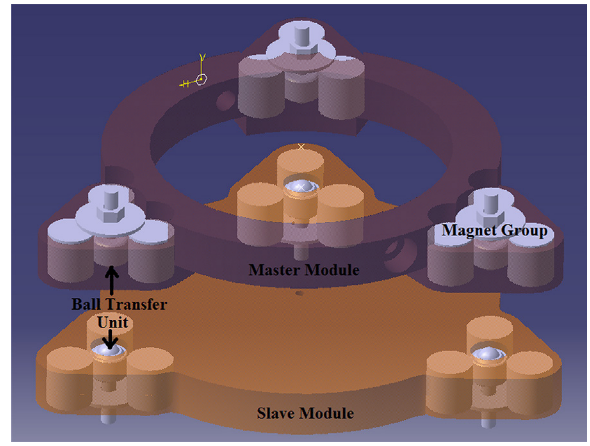

Fig. 3. Master on the top and slave on bottom, both of them consist of three magnet groups. Ball transfer unit is placed at the centroid of the equilateral triangle with magnets at its vertices.

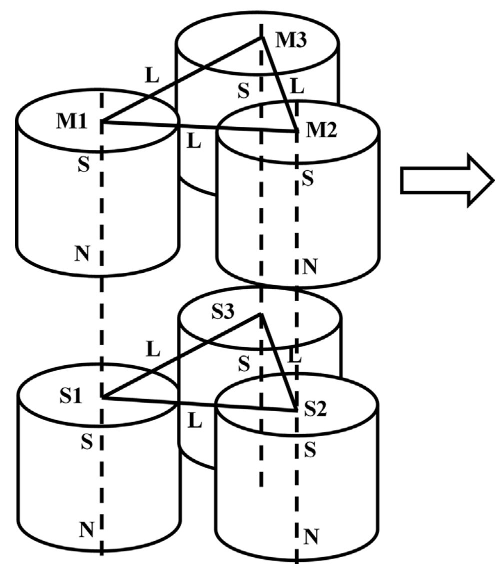

Fig. 4. A magnet group (M1, M2 and M3) in the master array coaxial to another magnet group (S1, S2 and S3) in the slave array in static (nominal) condition.

influence on that force as they are closely located. This was accounted for with the introduction of a force ratio representing the array contact force enhancement by Vokoun and Beleggia [8]. Furthermore, the member magnets of the other groups present in the array have influence on each other. However, as will be shown in the results section, such effects are negligible, due to the significant distance between the groups, and so will be ignored in the calculation. Only the influence of the magnets of the same group will be considered.

Vokoun et al. [6] expressed the axial attraction force F_z by zero order Bessel function of the first kind, $J_0(x)$ for two coaxial cylindrical permanent magnet of magnetization M, radius R, thickness t, axial gap x and lateral displacement r in Eq. (1) using aspect ratio $\tau_i = t_i/(2R)$, $i = 1, 2$ and $\zeta = (t_1 + t_2)/(2R) + x/R$.

$$F_z = -8\pi K_d R^2 \int_0^{+\infty} J_0\left(\frac{rq}{R}\right)\frac{J_1^2(q)}{q}\sinh(q\tau_1)\sinh(q\tau_2)e^{-q\zeta}\,dq \quad (1)$$

where the magnetostatic energy constant $K_d = \mu_0 M^2/2$.

In case of a group magnet instead of a magnet pair this Bessel function based equation was modified to include multiple magnets influence to the base pair attraction force. Vokoun et al. [6]