A Magnetically Adhering Wall Climbing Robot to Perform Continuous Welding of Long Seams and Non-Destructively Test the Welds on the Hull of a Container Ship

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Abstract-- The paper describes the development of a wall-climbing robot designed to carry a 7 DOF serial link robot arm of mass 22 kg to a maximum height of thirty metres on the outside surfaces of the hull of a container ship. The arm has been specially designed to perform remote inspection tasks. It deploys ultrasonic probes using force control and task error minimising control to perform pulse echo and Time-Of-Flight-Diffraction (TOFD) defect detection. The climbing robot is required to move on flat as well as curved surfaces and to step over 40 mm ridges that are formed by welding together steel plates of different thickness. The robot is currently being developed further to perform combined welding and monitoring of weld quality operations.

Index Terms-- wall-climbing robots, ship hull inspection, ship welding

I. Introduction

The hull of a typical container ship has external dimensions of typically 30 m height, 30 m width, 300 m length and a perimeter area of some 200,000 sq. m (0.2 sq. km). The hull is assembled by welding together several vertical sections, from bow to stern, in an open-air dry dock. Safety societies demand that 100% ultrasonic testing should be performed on these welds. This represents the welding and inspection of some 0.5 km of weld line between the hull sections on the external surface of the hull. The length of time taken for human operators to perform all of this welding and inspection has obvious implications for high labour costs and high incidence of fatigue-induced mistakes. The container ship building industry is fiercely competitive and would benefit from automation of the welding and inspection tasks [1]. Automating these tasks with large gantry robots would provide the best technical solution but would be prohibitively expensive and would interfere with movement of handling cranes required to transport the sections into place. A more feasible approach is to develop mobile robots that can climb vertical and curved hull surfaces to deploy the welding or inspection tool with robotic arms. Although there have been many recent developments of climbing robots only a very few have the payload capability to carry industrial scanning and welding arms [2-4]. The climbing robot reported here has been prototyped to perform ultrasonic testing of the vertical welds and the cross welds on the outside of a ship's hull. It has the potential for doing the welding as well and hence represents a significant advance in the automation of shipbuilding operations.

II. Requirements

The robot is required to provide the following performance:

- Climb on vertical flat or curved surfaces of the hull of a cargo container ship (shown in Fig.3) whilst carrying a 22 kg 7 DOF arm and power and signal cables of mass 30 kg when the robot is at a vertical height of 30 m.
- Inspect the cross welds (shown in Fig.1) on the outside surface of the hull up to heights of 30 m. The welds are at most 20mm wide and 10 mm proud of the surface. Ship building safety societies demand 100% ultrasonic testing of the weld.
- Perform continuous welding of plates on the hull of a ship (seen as the major application by a number of shipyards). The welds are long and require multiple passes. Manual welding is normally done in V-grooves from the inside of the hull. For automation, the V-grooves would be turned to the outside and pinned on the

inside. A mobile climbing vehicle carrying a robotic arm and welding tool would then weld on the outside of the hull.

- The welding is required to be continuous during which the welding tool must not vibrate. Vibration would result in defects in the weld. The mass of the welding tool should be about 7 kg. The welding should be guided by a sensor system that follows the V-groove and allows real-time adaptation of the welding tool to curvature in the hull. In addition, the sensor system should guide the mobile vehicle in following the weld groove. The advantage of automating welding is that the process can be controlled accurately. Hence, a dynamic process controller should be developed that is used to set up and change welding parameters.

  Checking the quality of the weld on-line during the welding would be advantageous and should be included. A sensor system incorporated in the welding tool could look at the weld pool to detect quality (e.g. rust can result in weld cracks).

  The welding wire feeder (mass 15 kg) should be carried by the vehicle while the wire spool should be on the ground at a distance of 20-25 m. The wire feeder should be of the pulling type.

- The robot should be designed to minimise vibration during motion of the robot so that the joints of the 7 DOF arm experience minimum vibration both to protect the gears on the joints and to keep the inspection probes and welding gun as steady as possible.
- The robot should be able to step over a surface change of depth 50 mm distributed over 120 mm (shown in Fig.2. The step is due to change in thickness of wall plate from 40 to 90 mm).
- The robot should be able to remain safely on the hull with all power switched off. This feature will enable the robot to remain on the hull until all work is completed and will ensure safety of the robot and personnel working on other tasks in the event of a power failure.
- As compact a size as possible of the robot would allow it to be operated in constricted spaces and would make it easier to adapt to curved surfaces.

III. ROBOT VEHICLE DESIGN

A. Design of Climbing Robot to realise the requirements

To meet the above requirements a prototype robot has been built that employs permanent magnets to adhere to the outside surfaces on the hull of container ships. It carries a seven axis serial-link scanning arm specially designed for inspection tasks. The arm deploys a payload of contact ultrasonic sensors under force control. Figure 4 shows the climbing robot prototype on a mock up hull supplied by the Odense Steel Shipyard in Denmark. Four linear ball bearing screw slides are used as the four "legs" of the walking robot. A load bearing platform that carries a 7 DOF manipulator is attached to the sliding block of each slide. The "foot" of each slide comprises of a pot magnet of size 65mm x 65 mm x 20 mm. Forward/backward motion of the robot is via two electric linear motors whose thrust blocks are rigidly tied together. The robot’s direction is changed by rotating it with a rotary screw actuator.

B. Rationale for the Design

Choice of pneumatic or electric actuators and also of pneumatic/vacuum suction or magnetic adhesion to a surface:

An initial design decision for a wall-climbing robot is whether to use magnetic or pneumatic adhesion. Pneumatic adhesion is preferred because it works on any type of material in principle. Also, pneumatic cylinders provided the lightest actuator and the best weight to power ratio for the linear motion of wall climbing robots. However, a factor that prevents the use of pneumatic propulsion and also adhesion is that it is very difficult to precisely control the position of the pneumatic cylinder and to prevent periods of transient vibration during motion and when releasing and picking up the suction cup feet. Thus a continuous welding operation as the vehicle moves would be impossible and weld defects would be introduced.

Linear screw slides or linear electric motors offer precise position controllability can produce the large power required to propel the envisaged heavy payload. Such fineness of spatial control is essential to achieve a continuous and thus minimal defect welding process. Although screw driven linear slides have advantages of low cost and in-built brakes, they require gearboxes and transmission components to drive the slide. Linear motors have the advantage that they are more compact than motor driven screw slides as electric motor/gearbox/encoder combinations on the end of the slide are eliminated and they are more accurate because of the elimination of backlash from gear boxes and transmission drives. The disadvantages of linear motor slides as compared to pneumatic linear slides are that they are very expensive, need PWM amplifiers, large robotic cables for 3-phase power and commutation and are much heavier.

The linear motor cannot be braked. However, the design of the vehicle can ensure that in the home position, brakes are not necessary, with the magnetic feet performing this function.

A drawback of the linear motor actuated vehicle may be the powerful magnetic rods in the motors and the magnetic feet. In an industrial environment this could cause problems by attracting tools, loose ferrous components, or ferrous equipment worn by workmen. Enclosing the robot in a shell that keeps sufficient distance between loose objects and the magnetic rods in the linear motors can reduce this danger. However, the magnetic feet cannot be similarly isolated.

Choice of walking mechanism or a wheeled mechanism:

Current magnetically adhering wall climbing inspection robots are invariably designed with wheels [5-8]. Although a wheeled vehicle provides greater speed and smoothness of motion and requires fewer actuators than a walking mechanism, wheels provide a small area of contact with the surface being climbed. Surface grease or grit can cause slippage of the driven wheels.

There are two ways in which permanent magnets can be used in a wheeled vehicle.

The permanent magnets can be kept at a fixed distance from the surface with rubber wheels providing the traction forces for motion. Design calculations show that a very large vehicle would be required to provide sufficient anti-sliding and anti-overturning moments for the very large payload specified earlier. The force of adhesion provided by permanent magnets falls off very rapidly (as the inverse of the square of the magnet/surface gap). Since the cross welds on the hull of a ship stand proud (up to 10 mm), the magnets would have to be positioned at a stand-off of at least this distance. The robot would have to be loaded with a large number of permanent magnets to obtain the required forces and moments. Also, wheeled vehicles need a turning circle, thus making the following of cross welds more difficult.

The other way to use permanent magnets is to employ magnet wheels or tracked wheels in which the track is composed of permanent magnet sections. In this case the magnets are in contact with the surface and hence provide a larger adhesion force. The tracked wheels make the following of cross welds and manoeuvring more difficult as they require a turning circle.

To summarise our design arguments so far there appears to be an overwhelming case to opt for a vehicle which moves by means of feet with magnetic adhesion, as opposed to conventional practice whereby magnetically adhering vehicles have wheels and pneumatically adhering vehicles, of course, have feet.

IV. Robot Vehicle Development

The development therefore has proceeded to build a walking robot that uses permanent magnets as its feet and picks and places these feet on the surface. Linear screw slides are used to lower or lift the magnets. Putting the magnets squarely in contact with the surface gives the maximum payload carrying capability for a given surface area of magnets. The ability to lift the magnetic feet off the surface under actuator control allows smooth and silent movement that does not damage the test surface. The ability to keep the feet at any desired distance from the surface allows the attraction force to be varied and permits obstacle avoidance e.g. weld profiles can be moved over and a good surface can be found before lowering the feet. Also uneven surface profiles are accommodated. The platform carrying the robot arm can be levelled if required by using the four independently controlled legs.

Also, while one set of feet are on the surface, the other set can be kept at a small stand-off to the surface to provide additional adhesion force.

The linear, accurately controlled slides allow precise accounting of the distance travelled for dead reckoning navigation and for surface mapping purposes.

Special attention has been paid in the design and selection of components for Electromagnetic Compatibility since the robot work cell is likely to experience interference from switching welding arcs.

The six axes of the climbing robot are implemented with Alan Bradley Ultra 100 drives. An RS Logix500 controller provides the option of controlling the axes with either Force, Velocity, or Position control. The linear motors use Digital Hall Effect Devices (HEDs) for phase initialisation and linear encoder feedback for commutation. At power up, the amplifier identifies the electrical phase sector that the motor is positioned in by looking at HEDs thus avoiding power-up phase searching.

A. *Robot dimensions and mass*

400 mm (max) length from front of robot to the back, 500 mm side to side, height 390 (max), nominal

distance of payload platform from the surface is 220 mm but can be lowered to 170 mm. Mass of total system is 127 kg which comprises of a 70 kg climbing robot + a 22 kg 7 DOF arm + a 5 kg arm payload + 30 kg of umbilical when the robot is at a height of 30 m.

B. Actuators for Forward/Backward Motion:

To keep the dimensions as small as possible without sacrificing the travel stroke of the robot two linear motors are used for the forward/backward motion. The stroke of each linear motor slide is 285 mm. The thrust blocks of the motors are tied rigidly together. The payload platform is transported by these thrust blocks. The peak force delivered by each motor is 500 N (10 A peak current) thus permitting a total force of 1000 N. The peak force can be applied for a maximum time of 30 s. During motion only half the design mass (63.5 kg) is transported at any one moment. Therefore the payload can be lifted up a vertical surface. Careful consideration has been given to the cycle time and r.m.s. force requirements of the linear motors so that thermal shut down and damage to motors is prevented. Controller fault conditions check these parameters and disable the drives if exceeded. The positioning accuracy of the linear motor slide is very high due to the fact that there is no gear box and hence transmission errors and is limited by the linear encoders used. Magnetic linear encoders rather than optical are used in the prototype to cope with a dirty environment. The positioning accuracy is 5 microns.

C. Magnetic Feet for Adhesion

The magnetic adhesion is by rare earth permanent magnets constructed into a steel magnet pot to protect the brittle magnets and to increase the holding force by closing the magnetic circuit. Currently the robot has eight feet with each foot each comprising of one magnet pot. Each foot of the robot is designed to provide:

- A minimum foot print so that small surface curvatures can be tolerated. This is achieved by a foot cross sectional area of 65 x 65 square mm. The foot is a block of mild steel that houses a rare earth permanent magnet of size 50 x 50 mm. The mild steel block performs two functions- It protects the brittle magnet against impact shocks and it closes the magnetic circuit to increase the holding force of the magnet.

- A maximum holding force to counteract overturning moments and a maximum anti-sliding force to prevent the design mass of 127 kg from sliding down the surface. The holding force of each magnetic foot has been measured while holding a 20 mm thick mild steel block, see figure 5. The normal holding force is more than 2000 N with a zero air gap (i.e. the magnet pot is in contact with the surface). An air gap of 3 mm produces a normal holding force of 700 N. The operating point of the magnetic foot is expected to be within this range and represents the two cases when a flat surface results in zero air gap between the foot/surface and when a curved surface results in worst case gap of 3 mm over all part of the foot. In practice the legs of the robot can raise/lower the feet so that some part of each foot is always in contact with the surface but for ball park figures determined below we will assume that in the worst case all feet have an air gap of at most 3 mm at the same instant of time.

1) Stationary operating point

8 feet are placed on the surface to provide a holding force in the range 16000 N (zero air gap) to 5600 N (3 mm air gap). The sliding force due to design mass of system = 1270 N. Assuming a worst coefficient of friction between mild steel and steel ship surfaces of 0.5 (coefficient of dry friction between hard steel surfaces is 0.7) the anti-sliding force available from the eight feet is 8000N (zero gap) - 2800 N (3 mm gap). Hence the safety factor S varies between S = 6 (zero gap) to 2 (3 mm gap). The robot is therefore guaranteed not to slide down the hull provided the total air gap due to surface irregularities does not exceed 3 mm on all the feet at the same time.

2) During motion

Four feet are alternately picked up from the surface and moved to a new position. The robot adheres to the surface via the other four feet. Hence, the anti-sliding force is due to four magnetic feet. The safety factor then reduces to S = 3 (zero air gap) to S = 1 (3 mm air gap).

The large holding forces provided by the permanent magnets are also necessary to overcome overturning moments due to the geometrical configuration of the robot arm and the climbing vehicle. With the current dimensions of the robot an anti-overturning safety factor of two is obtained with four magnetic feet.

D. Climbing Robot's Safety

One set of the permanent magnetic feet are always in contact with the surface during motion and since they cannot be switched off by accident, complete safety of the robot is guaranteed. In addition power to the robot can be switched off at any time, e.g. between worker shift breaks, and the robot will remain in-situ till it is required to operate again. The robot control system in teleoperation mode is programmed to turn off all motion servo axes after one complete step in any direction. This feature saves energy.

E. *Lifting and placement of magnetic feet on steel surfaces*

The magnetic feet are lifted from the surface by pulling them off with screw slides. The design force available from the LZBB SKF roller bearing screw slides used in the prototype is 5000N. This has proved more than sufficient to lift the magnetic foot when the air gap is zero (2000N normal force). Design effort has focused on ensuring that axial and radial forces are not exceeded when the robot is operating on vertical surfaces and that the bending moments on the mechanical structure of the robot are minimised. Currently there is some vibration when the magnets are detached from a zero air gap. The vibration is entirely eliminated if a rubber material covers the magnets so that the air gap is 3 mm. Future improvements will focus on exploring the trade-off between air gap, structural oscillation and a safe holding force.

The legs of the robot comprise of 4 screw slides each with a maximum stroke of 115 mm. The legs can all move independently and the position of each foot can be precisely controlled thereby providing the possibility of adapting to uneven surfaces, curvatures, and stepping over obstacles less than 50 mm in height from the surface. Four brushless ac servomotors provide the drive for each screw slide. Torque is transmitted from the motor to the screw via a belt transmission system.

F. *Rotation of the climbing robot to change direction*

The robot can be rotated through any angle between 0 to 360 degree in a positive or negative direction. The direction of the robot is precisely controllable thereby meeting the requirement for the cross-weld inspection task i.e. the robot can rotate 90 degree left or right. A rotary screw driven by a brushless ac servomotor actuates the rotation. This rotation capability provides the means to perform on-line steering of the robot to track weld seams.

V. The Seven Axis AnsaldO Arm

The main design effort during development of this arm has been to achieve lightweight so that the payload of the climbing robot can be commensurately smaller. A seven-axis arm, as opposed to the more conventional 5 or 6, provides the best opportunity to emulate the skills of the human operator. An ultrasonic sensor and vision system mechanical interface has been engineered during the arm design so that all the wiring is run internally through the centre of the robot's links. The arm can be detached/attached to the climbing robot with a fast and easy mechanical locking system. This feature allows the two to be transported separately and assembled quickly in a few minutes. The 7-axis arm mass is 22 kg and its end-effecter can handle a 5 kg load. This load capacity is ample for the end-effecter to carry a typical three-element ultrasonic probe array and apply the requisite contact pressure, both for dry-contact wheel probes or conventional fluid coupled probes. One probe, acting as common transmitter- receiver covers normal incidence thickness measurements for corrosion monitoring. The other two probes act in tandem to perform weld inspection, in skip style, including both conventional amplitude measurements and time of flight diffraction measurements (TOFD). The design incorporates a water feeder and couplant retrieval system as an integral part of the arm. The arm was designed to cope with structural geometry much more complicated than the hull of a ship, namely the complex pipe-work occurring in nuclear power plant [9]. The arm is built with a force sensor in its wrist. The control architecture and methodology utilises this force sensor to deploy the ultrasonic payload for contact non-destructive testing on unknown surface profiles using a task function control scheme.

The end-effecter load capacity can be extended to cope with a typical weld tool weighing 7 kg.

To the author's knowledge this is the lightest 7 or even 6 axis arm to have a spatial position repeatability of better than one millimetre, as needed for non-destructive testing purposes, and with a control system designed to deploy probes on unknown surface profiles with a raster scanning trajectory.

The main mechanical characteristics of the arm are tabulated in table 1.

Tab.1 The ANSALDO Arm

Main Geometric/Kinematic Characteristics			
Joint No	Name	Velocity	Range
1	Turret	30° / sec	± 170°
2	Shoulder	30° / sec	± 170°
3	Elbow Row	45° / sec	± 180°
4	Elbow Pitch	45° / sec	± 150°
5	Wrist Roll	90° / sec	± 180°
6	Wrist Pitch	90° / sec	± 120°
7	Hand Roll	90° / sec	± 180°

Main Physical Characteristics	
Mass	22 kg
Payload	40 N
Arm Length	310 mm
Accuracy	1 mm

VI. FUTURE WORK

The current magnetic robot vibrates when the permanent magnets are pulled off the surface from a zero gap though as already mentioned this is almost negligible when the air gap is 3mm. A study is required on ways to modify the current vehicle to eliminate vibrations- there are several ways, e.g. by modifying the mechanical structure of the vehicle, by increasing the air gap between the magnets and the surface, by suitable control action, or by using electromagnets rather than permanent magnets, or by using a wheeled vehicle. The welding performance of the modified vehicle will be assessed for some or all of these solutions.

ACKNOWLEDGEMENT

The authors are indebted to the European Commission under grant number BE 3038 for the funding to implement the design concept described here into a prototype vehicle. They also gratefully acknowledge the helpful discussions with their project partners, OIS plc, Odense Steel shipyards, Ansaldo Nuclear Reserche, The Department of Information Science and Technology, University of Genoa, and SOGIN.

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Fig.1 Welds on the exterior surface of a hull, 20 mm wide and up to 10 mm proud of the surface

Fig.2 Horizontal steps, typically up to 40 mm high, in the external surface of the hull

Fig.3 Stern section of a hull, showing the smallest curvature to which the robot must adapt

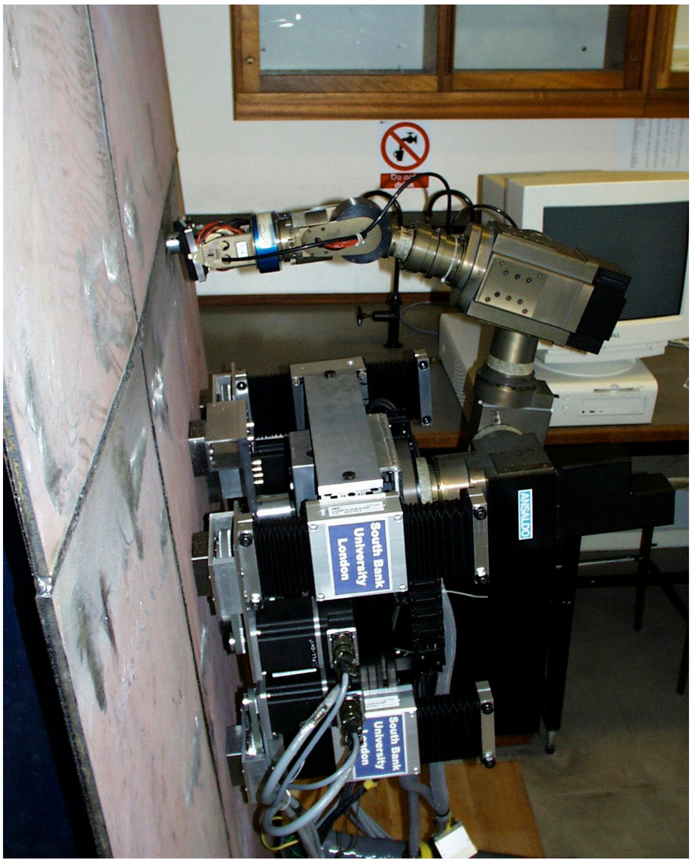

Fig.4 Climbing Robot Carrying the ANSALDO 7 DOF Arm on a Hull Mock Up

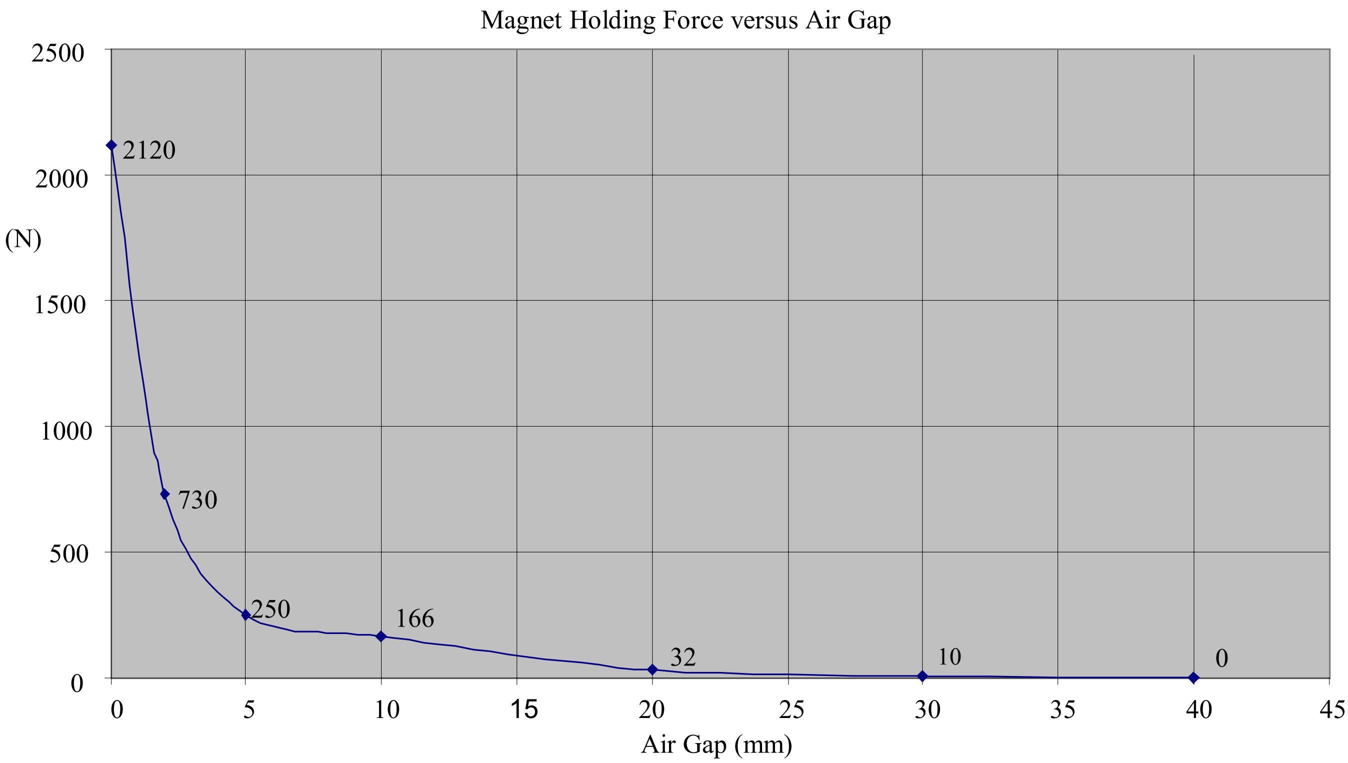

Fig.5 Holding Force versus Air Gap for a 65mm x 65mm Rare Earth Magnet