Examination of levitation of thin non-magnetic conductor by ac electoromagnet type electro dynamic suspension

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ABSTRACT: Because transportation by magnetic levitation has the advantage of not contacting, it has various good points. Conventional studies of EDS are aimed on the large-scale applications, and use the non magnetic conductor of 1mm or more in thickness. However, in theoretical, it is possible that the thinner non magnetic conductor of less than 1mm in thickness levitate, using higher frequency or larger magnetomotive force. Therefore, applications to a smaller levitation model can be expected. In this paper, the relation between lift force and the temperature rise in the conductor is examined from the numerical analysis, when we consider a smaller levitation model. Skin effect and electromagnetic force between gaps are taken into account. These results are verified by experiments.

1 BACKGROUND

Because transportation by magnetic levitation has the feature of not contacting, it has advantage according to flawless, high-speed and no dust. Moreover it excels also to use in special environment (clean room, inside of a vacuum). The method of magnetic levitation is divided into two kinds. It is categorized into the suction system which acquires lift force from magnetic power of absorption, and the rebounding system obtained from magnetic repulsion as the method of magnetic levitation. Electro dynamic suspension (EDS) belongs to the rebounding system. Since EDS is stable in the levitation direction, levitation of it by no perfect controlling is attained. The structure can be simplified because the sensor etc. is unnecessary.

EDS has two methods which use the permanent magnet or the ac electromagnet. In permanent magnet type EDS, it is necessary to perform relative movement between the magnet and the non-magnetic conductor. Lifting is difficult at the time of low speed and stop. As the example of studies, JR-Maglev of JR and Railway Technical Research Institute in Japan is famous. There is other Urban-maglev which General Atomics in USA is studying. In ac electromagnet type EDS, it is possible to lifting in the stillness state relatively between ac electromagnet to non-magnetic conductor. Therefore, it is suitable to conveyance for which levitation in the time of stillness and a low speed is needed. As the example of studies, there is the opposed type magnetic levitation conveyance device studied by Mitsubishi heavy industries. Either of the methods, the non-magnetic conductor generates heat by eddy current guided to a non-magnetic conductor. This affects lifting. There are few examples studied and utilization about transportation according to EDS in the present condition.

It is possible that the thinner non magnetic conductor of less than 1mm in thickness levitate in theoretical, using higher frequency or larger magnetomotive force. Furthermore, the large power more than levitation of the non-magnetic conductor can obtain. Then, using to levitation conveyance of the non-magnetic conductor itself or the conveyance subject using the thin non-magnetic conductor, and electromagnetic force actuator can be considered. The burden by the side of a power supply and increase of heat generated in the non-magnetic conductor, however, are problems in connection with the increase in a magnetic field or frequency.

In this paper, we attention to relation of a magnetic field required for lifting and frequency, and heat generated in the non-magnetic conductor. Generation of heat affects the resistivity of the non-magnetic conductor and lift force decreases as the result. The relation between a magnetic field and frequency also affects the burden to a power supply greatly. Then, these relations are compared from numerical analysis, and we consider lift force, generation of heat, and the burden to a power supply. Moreover, it verifies about lifting of aluminum foil with the thickness of 0.05 mm by experiment.

2 THE FREQUENCY CHARACTERISTIC OF THE MAGETOMOTIVE FORCE AND THE TEMPERATURE RISE

2.1 *The numerical analysis technique and the analysis conditions*

We use the impedance matrix calculation method proposed by Takahashi for numerical analysis. This method subdivides the non-magnetic conductor, and assumes each to be independent wire. We compute the eddy current by solving ac circuit equation from

the relations between a coil and a wire, a wire and a wire. Here, the following assumption is placed in this method.

· The non-magnetic conductor is uniform in the direction of x-axis, and the end effect is neglected.
· The current by the side of a coil is replaced with line current.
· A coil is sufficiently long in the direction of x-axis compared with the direction of y-axis.

Lift force is acquired from the relation of the magnetic field which intersects the computed eddy current. In order to take skin effect produced in the non-magnetic conductor and the influence of electromagnetic force between gaps into consideration, we add the correction to conductor thickness and gap length. The temperature rise in the non-magnetic conductor is searched for as follows. The generating quantity of heat in each wire can be found from the resistance and the eddy current. By adding the quantity of heat of each wire together, whole quantity of heat P (W/m) is obtained. Here, delay by heat conduction is disregarded. The temperature rise per second T_s (K/s) is computed by the equation (1).

$$T_s = \frac{P}{mc} \tag{1}$$

Where, m is the mass (g) and c is specific heat (J/g·deg. C) of the non-magnetic conductor.

The numerical analysis model is shown in Fig. 1. Table 1 shows the analysis model. Lift force is expressed as magnetomotive force NI (AT) required in order to levitate subjects to a certain frequency f (Hz). Moreover, we ask for the temperature rise T_s (K/s) in this case.

2.2 Levitation with an aluminum simple substance

We consider levitation of an aluminum simple substance. Fig. 2 is as the result of numerical analysis. An eddy current also increases with the increase in frequency from Fig. 2. Therefore, required magnetomotive force decreases and draws the characteristic in inverse proportion to frequency. If it becomes the region of high frequency, under the influence of skin effect, an eddy current will be saturated and lift force will also be saturated. Required magnetomotive force differs because the eddy current changes with thickness in the non-saturated region. When weight is light, required magnetomotive force should decrease. Required magnetomotive force, however, increases from the eddy current decreasing. The value of lift force is not dependent on thickness in the saturation region and saturated in the almost same value. Therefore, required magnetomotive decreases, so that it is lightweight.
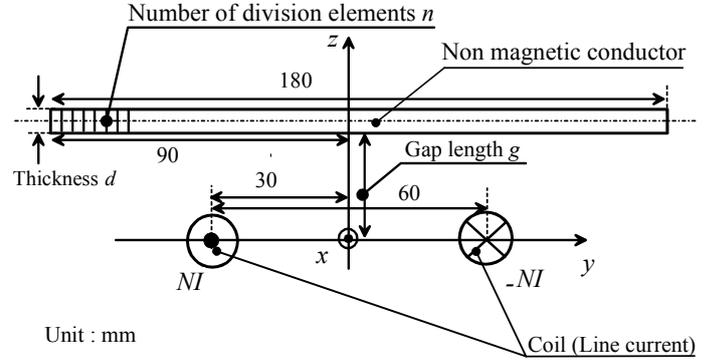

Figure 1: Numerical analysis model

Table 1: Numerical analysis condition

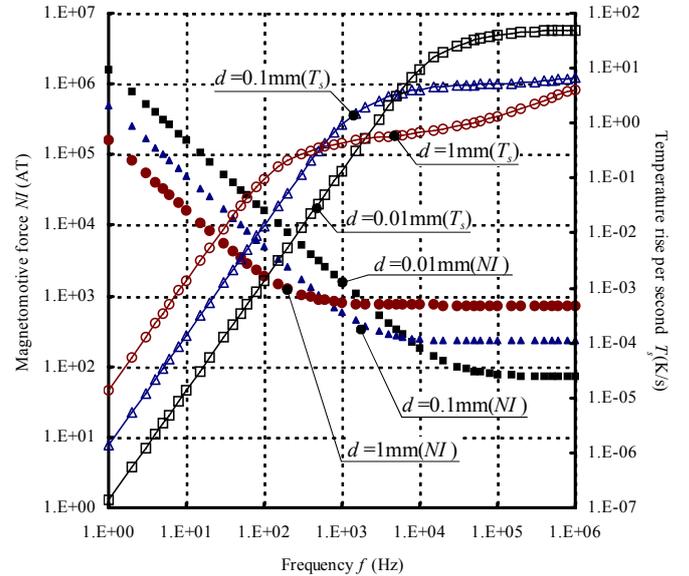| Thickness of conductor : d (mm)		1, 0.1, 0.01
Gap length : g (mm)		10
Number of division elements : n		500
Temperature : t (deg. C)		25
Conductor		Al, Cu, Ag
Density of conductor : de (g/cm³)	Al	2.67
	Cu	8.96
	Ag	19.32
Resistivity of conductor : ρ ($\mu\Omega$·cm)	Al	2.76
	Cu	1.72
	Ag	1.62
Specific heat : c (J/g·deg. C)	Al	0.905
	Cu	0.386
	Ag	0.237

Figure 2: Frequency characteristic of magnetomotive force necessary for only Aluminum lifting and temperature rise per second

The quantity of generated heat also rises from the eddy current increasing with the increase in frequency. Therefore the temperature rise draws the characteristic proportional to the second power of frequency. Since the eddy current to generate is

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saturated, the temperature rise is also saturated with the high frequency region. The temperature rise, however, is increasing again by the increase in frequency. This is based on the thickness correction for taking skin effect into consideration. The quantity of heat changes with the eddy current and the thickness of the non-magnetic conductor in the non-saturated region. Because the eddy current decreases in the case of the thin non-magnetic conductor, a temperature rise also decreases. In the case of the thin conductor, a temperature rise is high in a saturation region because the volume of the non-magnetic conductor differs. The temperature rise by the eddy current can be decreased on low frequency in the non-saturated region. However, levitation is required in large magnetomotive force and the burden by the side of the power supply containing a coil increases. If frequency is made high, required magnetomotive force will decrease. Since the eddy current increases, the temperature rise also increases. These results show that magnetomotive force and the temperature rise are the relations of trade-off. The increase in magnetomotive force is the burden to a power supply or a coil. The temperature rise of the non-magnetic conductor affects lift force. Because it does not contact, heat dissipation is difficult. We should take the temperature rise into consideration preferentially when long levitation time is taken.

2.3 Levitation in the case of adding aluminum and load

Levitation in the case of putting a semiconductor wafer on aluminum as load is considered. An actual wafer is circular. On numerical analysis, it is assumed that silicone substrate covers the whole surface of the non-magnetic conductor. Here, in consideration of heat moving to the wafer which is a conveyance subject from the non-magnetic conductor, the temperature rise is calculated. However, it supposes that heat transfer is performed quickly enough, and heat transfer into air is neglected because compared with semiconductor wafer. Thickness of silicone is set to 0.5 mm, density is made into 2.33 g/cm^3 and specific heat is made as 0.713J/g · deg. C.

Fig. 3 shows the result of numerical analysis. Required magnetomotive force is increasing on the whole compared with Fig. 2 in order to support the load of about 2 N/m. The difference of magnetomotive force spreads because acquire the lift force for load in the non-saturated region. Required magnetomotive force also serves as the almost same value because lift force is saturated in the saturation region. In the characteristic of d=1 (mm), the mass of the non-magnetic conductor is larger than load and becomes dominant. Therefore, saturation values differ greatly.
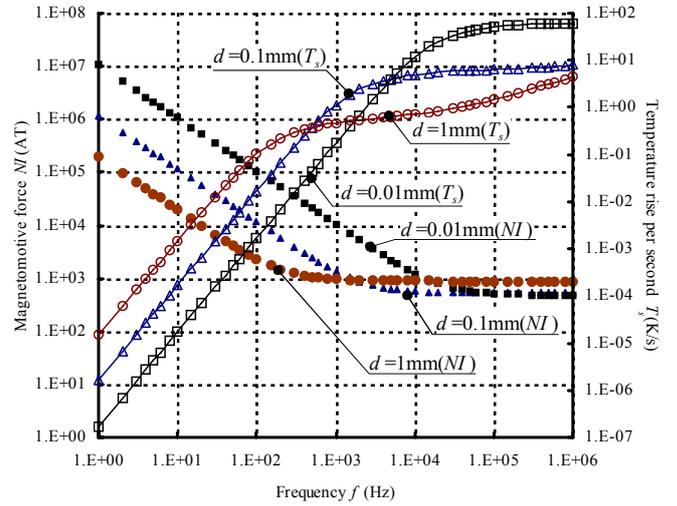

Figure 3: Frequency characteristic of magnetomotive force necessary for Aluminum and load lifting and temperature rise per second

2.4 Levitation using various conductors

We search for each frequency characteristic about three kinds of non-magnetic conductors (aluminum, copper, silver) with which density, resistance and specific heat differ. It gropes for the optimal conductor for levitation from these conductors. Numerical analysis is performed about d=1 (mm) and 0.01 (mm) on the same conditions as Section 2.3.

Fig. 4 and Fig. 5 are as the result of numerical analysis. From Fig. 4, since weight of a conductor is dominant, it turns out that the characteristics in which the light aluminum of weight is excellent in magnetomotive force and the temperature rise are drawn. Therefore, it turns out that aluminum is suitable for levitation. From Fig. 5, the difference of each characteristic becomes small in order to load is heavier than the mass of the non-magnetic conduc-
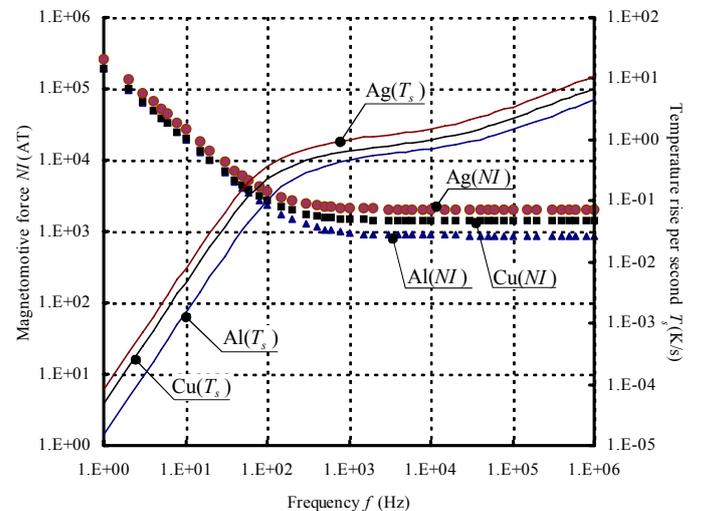

Figure 4: Frequency characteristic of magnetomotive force necessary for conductor and load lifting and temperature rise per second (d=1mm)

tor. This is based on the relation between the rate of

resistance and the mass of a levitation conveyance thing. The required magnetomotive force of copper is small in the non-saturated region, and aluminum is the largest on the contrary. The temperature rise, however, has least aluminum. Required magnetomotive force of aluminum is the smallest in the saturation region. It is copper that the temperature rise becomes the smallest. Here, the optimal conductor changes with how to put emphasis. If it thinks stopping magnetomotive force as important, the non-magnetic conductor with the low rate of resistance is suitable. If it thinks suppressing generation of heat as important, the conductor of small specific gravity is suitable.
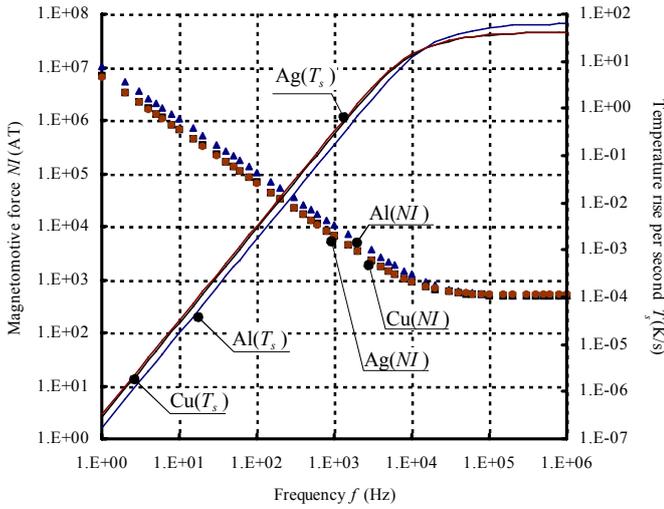

Figure 5: Frequency characteristic of magnetomotive force necessary for conductor and load lifting and temperature rise per second (d=0.01mm)

3 TEMPERATURE OF NON-MAGNETIC CONDUCTOR AFTER FIXED TIME, AND CHANGE OF GAP LENGTH

When frequency and magnetomotive force are fixed, time change of the temperature in non-magnetic conductor and gap length is computed in numerical analysis. Time restriction of levitation should be known from there. In numerical analysis, the setup of the temperature in the non-magnetic conductor and the rate of resistance are corrected in consideration of the temperature rise per second. And lift force analysis is repeated and is conducted. Here, reduction of the lift force by temperature rise of a conductor is expressed as change of gap length. The numerical analysis model is the same as Fig. 1. The numerical analysis conditions at the time of a levitation start use Table 1. The conductor to be used sets up aluminum. Frequency and magnetomotive force use the value acquired by Section 2.2 and Section 2.3.

Fig. 6 shows the numerical analysis result of only aluminum. Fig. 7 shows the numerical analysis result at the time of adding load like Section 2.3. From Fig. 6 and Fig. 7, conductor temperature settles down around 200 deg. C. On the other hand, it continues increasing in d= 0.01 (mm) and exceeds 660 deg. C. which is a melting point of aluminum near 40 kHz. However, it turns out that d= 0.01 (mm) is lower as for a temperature rise irrespective of load up to near 6kHz. Moreover, it turns out that gap length becomes the minimum on a certain frequency. The minimum gap length is taken near 2 kHz in d=0.1 (mm), and 40 kHz in d=0.01 (mm). This is the result of being based on the reactance component in a high frequency region and the increase in the rate of resistance by the heat produced in the non-magnetic conductor. The temperature rise increases as the setting value of frequency increases. Therefore, reduction of lift force is carried out because the rate of resistance increases. And gap length becomes short. The reactance, however, becomes dominant from resistance by lift force analysis in the high frequency region. Accordingly, lift force almost stops influencing by temperature rise. Maintenance of gap length becomes difficult previously rather than temperature on frequency with gap length's large change. Thus, we calculate temperature of conductor and gap length in time, and we are able to know the time limit of levitation.
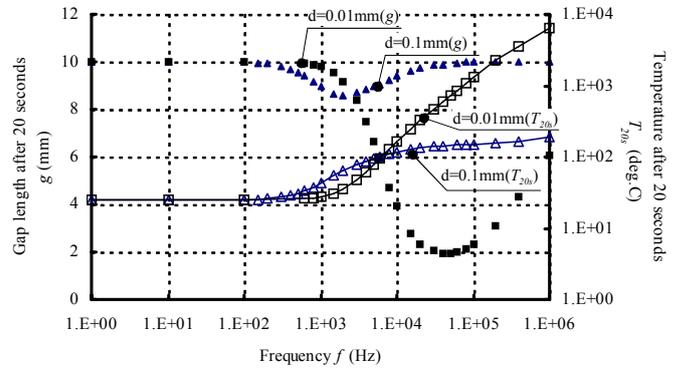

Figure 6: Frequency characteristic of gap length and temperature of conductor after 20 seconds in lifting only of aluminum
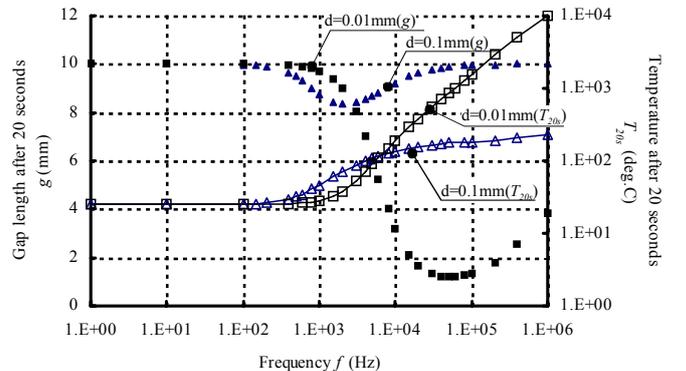

Figure 7: Frequency characteristic of gap length and temperature of conductor after 20 seconds in lifting of aluminum and load

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4 EXAMINATION ABOUT LEVITATION AND POWER SUPPLY CAPACITY

4.1 The frequency characteristic of power supply capacity

We calculate power supply capacity required for per unit square millimeter of the non-magnetic conductor in each frequency based on Section 2.3. We have placed the parallel coil with line current infinitely in the direction of x-axis on the numerical analysis model from the assumption in the impedance matrix method. Then, this line current is assumed to be the copper wire (1.72 μΩ・ cm) 0.5mm in diameters. So, the resistance is 0.022 Ω/m and the inductance is 2.24 μH/m. We ask for the synthetic impedance in each condition, and power supply capacity P (VA/mm^2) required for per unit square millimeter on levitation of the non-magnetic conductor is derived. P is computed by equation (2).

$$P = 2I^2 Z_l /(180 \times 1000)$$
$$\left(Z_l = \sqrt{R^2 + (2\pi f L)^2} \right) \tag{2}$$

Fig. 8 shows the numerical analysis result. Power supply capacity takes the minimum value on a certain frequency. This is based on the increase in the reactance component of a coil. Required magnetomotive force for levitation is saturated with the saturation region of lift force. Since the reactance of a coil is proportional to frequency, required power supply capacity increases with the increase in frequency.
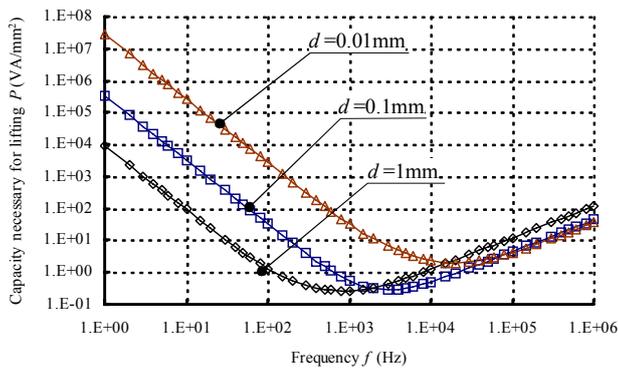

Figure 8: Frequency characteristic of capacity of power supply required for Aluminum and load lifting

4.2 Thickness of conductor and power supply capacity

We place with f_p (Hz) the frequency from which power supply capacity required for levitation serves as the minimum. The relation between conductor thickness and frequency f_p is considered based on Section 4.1. Fig. 9 shows the numerical analysis result. From Fig. 9, f_p becomes high as the thickness of

a conductor becomes thin. Although this value is changed according to the conditions of the resistance or the inductance, f_p exists in any conditions. Then, levitation on the frequency beyond f_p causes not only the increase in generation of heat but the burden to power supply capacity increases. Therefore, it is desirable to levitate in the frequency below f_p whose relation between generation of heat and power supply capacity is trade-off.
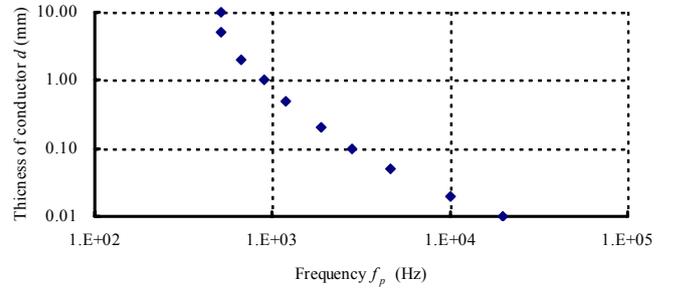

Figure 9: Relation between conductor thickness and frequency with the smallest power supply capacity required for excitation

5 THE MEASURING DEVICE OF LIFT FORCE USING ALUMINUM FOIL

5.1 The experimental device and the measuring method

Based on the result of numerical analysis, the lift force produced in aluminum foil is measured, and it verifies about levitation. Fig. 10 shows the measuring device of lift force. Fig. 11 is the structural drawing of this. The non-magnetic conductor uses aluminum foil (0.05 mm in thickness). The silicon wafer is 3 inches (76.2 mm) in diameter, and 0.5 mm in thickness. Hooks are attached to four on the wafer on the basis of square aluminum foil, and these hang with springs. The whole experimental system is shown in Fig. 12. From Fig. 12, the inverter is connected to a coil and this performs adjustment of frequency in a coil and current. The inverter uses VAH-3LF6 (Hitachi Industrial Equipment Systems, 5 kHz in maximum frequency). The current which
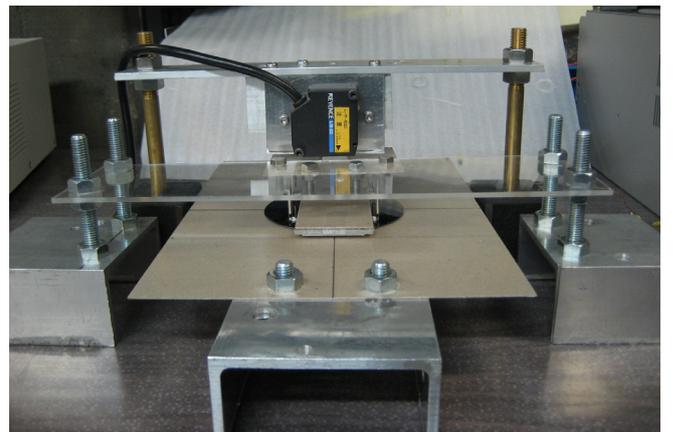

Figure 10: Lift force measurement device