Effect of the Intermolecular Forces on the Flying Attitude of Sub-5 NM Flying Height Air Bearing Sliders in Hard Disk Drives

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ABSTRACT

When the spacing between the slider and the disk is smaller than 10 nm, the effect of the intermolecular forces between the two solid surfaces can no longer be ignored. This effect on the flying attitude of practical slider designs is investigated here numerically. The 3-D slider surface is discretized into non-overlapping unstructured triangles. The intermolecular forces between each triangular cell of the slider and the disk surface are formulated, and their contributions to the total vertical force, as well as the pitch and roll moments, are included in a previously developed steady state air bearing design code based on a multi-grid finite volume method with unstructured triangular grids [3-5]. It is found that the van der Waals force has significant influence on the flying height and has non-negligible effect on the pitch angle for both positive pressure sliders and negative pressure sliders, when the flying height is below 5 nm. When the flying height is below 0.5 nm, the repulsive portion of the intermolecular force becomes important and also has to be included.

INTRODUCTION

The air bearing sliders in today's hard disk drives must fly lower and lower to achieve higher areal density. The spacing between the read-write element at the trailing edge of the slider and the disk surface where magnetic information is stored plays a significant role in the system's performance. Traditionally, the flying attitude of the slider (including the flying height, the pitch and roll angle) is determined by the balance of force and moments contributed from the pre-load of the suspension and the air bearing pressure and shear. The pre-load force and moments from the suspension are assumed to be known. Most studies of air bearing simulations are concerned with the modifications of the Reynolds lubrication equation in order to get reasonably accurate predictions of the air bearing pressure field under rarefied conditions and also the numerical methods that can solve this equation efficiently. To increase the areal density to the range of 1 Tbit/in^2, a flying height around 3nm is believed to be necessary. At such a low spacing, additional physical phenomena that are not important and have been ignored when the slider flies above 10 nm become increasingly more important and may no longer be negligible. For example, the intermolecular forces between the two solid surfaces of the slider and the disk tend to attract them when the distance is less than 10 nm and repel them at sufficiently small spacing. These forces participate in the balancing process and may have an important influence on the flying attitude of the slider, both statically and dynamically.

For a slider with a flying height around 0.4 to 5 nm, among these forces, the long range attractive van der Waals force is the dominant one, which has an effective range from 0.2 nm to a distance greater than 10 nm. It is contributed mostly from the dispersion force between two atoms, which is induced by the fluctuations in their electric dipoles. The instantaneous positions of the electrons around an atom generate a finite dipole moment, even though the time average is zero. The electric field generated by the finite dipole moment of one atom also induces a dipole moment in the other atom. This makes the two atoms attract each other. A detailed explanation and theory can be found in [1].

A previous preliminary investigation using a simplified geometry showed that the van der Waals force changed the load capacity significantly when the bearing spacing is low enough [2]. For a positive pressure flat surface slider with zero roll angle, these authors numerically showed that the van der Waals force causes a lower limit clearance of a few nano-meters, below which the load capacity becomes negative. This clearance limit decreases with the pitch angle [2]. They did not investigate the effect of the van der Waals force on the slider's flying attitude and they ignored the repulsive portion of the intermolecular force. When the spacing is extremely low, this portion of the intermolecular force needs to be included; otherwise the slider would never take off, because at actual contact the purely attractive van der Waals force is extremely large. In addition, to fully understand its effect on the design goal in hard disk drives, more practical and complicated sliders need to be examined, including negative pressure sliders. Since the load capacity of negative pressure sliders is quite different from that of the positive pressure slider, we expect different results or trends between them.

Here we extend the investigation in [2] by first formulating the total intermolecular force between an infinite plate and a triangular cell of material of the slider that has a relatively large vertical thickness compared to the acting range of the forces and is oriented in 3-D space. The 3-D air bearing surface is then meshed into triangles. The total force and the pitch and roll angle moment contributions from the intermolecular forces between the slider and the disk surface are calculated and incorporated into the previously developed steady state air bearing design code [3-5]. The intermolecular force effects on the load capacity and flying attitude are demonstrated for particular examples of a positive pressure Tripad slider and a negative pressure Femto slider.

THE INTERMOLECULAR FORCE BETWEEN THE SLIDER AND THE DISK

When two atoms are brought close enough, they start to experience the existence of each other in the form of intermolecular forces. At the beginning, it is an attraction force, and its strength increases with decreasing distance until a maximum point is reached, then it decreases with decreasing distance. When the distance is reduced further, the force becomes repulsive and increasingly stronger. This is reflected in Fig. 1, which shows the potential energy between two atoms as a function of their distance. One expression used to describe this potential is the so called Lennard-Jones potential, in which the attractive van der Waals potential is modeled as an inverse sixth power term and the repulsive potential is modeled as a inverse twelfth power term

$$w = -\frac{C}{r^6} + \frac{D}{r^{12}}, \qquad (1)$$

where $C = 10^{-77}\, Jm^6$ and $D = 10^{-134}\, Jm^{12}$ are two constants for atoms in vacuum [1]. For sliders flying with a few nano-meters spacing, the repulsive potential term can be ignored, and we obtain the purely van der Waals potential

$$w = -\frac{C}{r^6} \,. \qquad (2)$$

Equation (1) is the potential between two atoms, and it can be integrated over an infinitely long and infinitely deep half space to obtain the potential between an atom and an infinite plate,

$$W = -\frac{pC r_1}{6h^3} + \frac{pD r_1}{45h^9} \,, \qquad (3)$$

where r_1 is the number density of atoms in the infinite plate, and h is the distance between the atom and the plate. Equation (3) can be integrated over a volume of material within the slider, which has a triangular intersection area with the air bearing surface, to obtain the total interaction potential between the volume of material of the slider and the infinite plate

$$W_v = -\frac{pC r_1 r_2}{6} \iint_{\Delta} dxdy \int_h^{\infty} \frac{1}{z^3} dz + \frac{pD r_1 r_2}{45} \iint_{\Delta} dxdy \int_h^{\infty} \frac{1}{z^9} dz \,, \qquad (4)$$

where r_2 is the number density of atoms within the slider. In Eqs. (3) and (4), to simplify the problem, the depth of the plate and the thickness of the slider have been taken to be infinite. This is justified, since the actual depth of the plate and the thickness of the slider are several orders larger than the acting range of the intermolecular force. By defining the Hamaker constant as $A = p^2 C r_1 r_2$ and another constant $B = p^2 D r_1 r_2$ and carrying out the integration in the z direction, we obtain

$$W_v = -\frac{A}{12\pi}\iint_{\Delta}\frac{1}{h(x,y)^2}\,dxdy + \frac{B}{360\pi}\iint_{\Delta}\frac{1}{h(x,y)^8}\,dxdy\,. \tag{5}$$

To obtain the intermolecular force between each triangular volume of material of the slider and the plate, we need to differentiate the potential of Eq. (5) in the direction perpendicular to the plate. After that, the intermolecular force between each triangular cell and the disk can be written as

$$F_v = \frac{dW_v}{dz} = \frac{A}{6\pi}\iint_{\Delta}\frac{dxdy}{h^3} - \frac{B}{45\pi}\iint_{\Delta}\frac{dxdy}{h^9}\,. \tag{6}$$

The first term on the right hand side of Eq. (6) is the attractive van der Waals force, and the second term is the repulsive intermolecular force. The attractive and repulsive portions of the force have different acting ranges. The attractive van der Waals force has a much longer acting range than the repulsive portion. The two solid surfaces first experience the attraction force when the distance between them is less than about 10nm. The strength of the attractive force increases with the reduction of the spacing until the spacing becomes small enough such that the short range repulsive force becomes active. We can roughly estimate the acting range of the repulsive intermolecular force by equating the attraction potential and the repulsive potential in equation (1)

$$\frac{C}{r^6} \sim \frac{D}{r^{12}}\,. \tag{7}$$

The above equation gives

$$r \sim \left(\frac{D}{C}\right)^{\frac{1}{6}} \approx 0.32\ nm\,. \tag{8}$$

This is roughly the spacing, below which the repulsive force can not be ignored.

THE NUMERICAL SOLUTION OF THE BALANCED STEADY STATE ATTITUDE

The Quasi-Newton iteration method for non-linear problems, described in Dennis and Schnabel [6], is implemented to find the steady state flying attitude. We can define an objective vector $\underline{R} = (R_1, R_2, R_3)$ with

$$R_1 = F_{air} - F_s - F_v, \qquad (9)$$

$$R_2 = (M_{air})_p + (M_s)_p + (M_{shear})_p + (M_v)_p, \qquad (10)$$

$$R_3 = (M_{air})_r + (M_s)_r + (M_{shear})_r + (M_v)_r, \qquad (11)$$

where F_{air} is the resultant air bearing force of a guessed flying attitude, F_s is the applied suspension force, F_v is the attractive van der Waals force, M_{air}, M_{shear}, M_s and M_v are moments caused by air bearing pressure, viscous shear force at the slider air bearing surface at that guessed attitude, the suspension and the van der Waals force, respectively. The air bearing contributions are found by numerically solving the Reynolds equation [3-5]. The suspension contributions are known. The van der Waals force contributions are obtained by summing up the forces evaluated by Eq. (6) and its moments in each triangular cell. A 7-points quadrature (Fig. 2) is used to evaluate the integration in Eq. (6). The steady state attitude corresponding to null $\underline{R}$ is obtained by a few iterations.

RESULTS

In the simulations, the Hamaker constant A is taken to be $10^{-19} J$ and the constant B is taken to be $10^{-76} Jm^6$, which are typical values for interactions between condensed phases across vacuum or air (the Hamaker constant is in the range 0.4-$4\times10^{-19} J$ for most condensed phases) [1]. The first slider used to demonstrate the van der Waals force effect is the posititve pressure Tripad nano slider (Fig. 3) with a 3.5g force and zero moment pre-load from the suspension. The disk rotation speed is 5400 rpm. Figure 4 shows the different force contributions to the load as a function of the flying height at a fixed pitch angle of $150 mrad$ and zero roll angle. Without the van der Waals force, the total air bearing force curve coincides with the positive air bearing force curve, since the negative air bearing force is negligible for this design. The total load capacity increases with decreasing flying height. However, if the van der Waals force is included, the total load curve starts to deviate from the positive air bearing force curve at a flying height around 3 nm, which corresponds to the height at which the attractive van der Waals force becomes significant, and it no longer increases but instead decreases with decreasing flying height. Below 1 nm, the total load curve bends down and decreases rapidly. As the flying height is reduced further, it becomes negative, which means the slider can not sustain any load. The flying height corresponding to zero load capacity is what is called the low limit clearance in [2]. As a result, the van der Waals force changes the total load curve at flying heights below 3 nm. In Fig. 5, the different force contributions and the total loads have been ploted as functions of the pitch angle. The flying height is fixed at 0.45 nm, and the roll angle is zero. Without the van der Waals force, the total load curve coincides with the positive air bearing force curve and increases with decreasing pitch angle. But the attractive van der Waals force also increases with decreasing pitch angle. The net effect is an almost zero total load capacity at all pitch angles shown. Figure 6 shows the flying height of the Tripad slider at different radial positions. The van der Waals force lowers the flying height from 4.73 nm to 3.71 nm at the inner radius (15 mm), which is a 21.6% reduction. At the outer radius, the difference is negligible, since the flying height is out of the acting range of the van der Waals force. Figure 7 shows the van der Waals force effect on the pitch angle of the Tripad slider at different radial positions. At the inner radius, the van der Waals force slightly increases the pitch angle. Again, it has negligible effect at the outer radius. Figure 8 shows that the van der Waals force has negligible effect on the roll angle.

Figure 9 shows a negative pressure Femto slider design for a 0.5g suspension force and zero moment suspension pre-load and a disk rotation speed of 7200 rpm. Figure 10 shows the force contributions to the total load as a function of the flying height. The pitch angle is held at $150 mrad$, and the roll angle is zero. The negative air bearing force is almost constant with distance, so the total load increases with the positive air bearing force as the flying height is reduced, if the van der Waals force is not included. But when including of the van der Waals force, the total load curve starts to deviate from the curve without van der Waals force at a height of about 5 nm. Below 5 nm, the total load decreases slowly at the beginning, and then decreases rapidly and becomes negative when the flying height is reduced further. There is also a low limit clearance for this slider. Figure 11 shows the force contributions to the total load as a function of the pitch angle for the flying height fixed at 4 nm. The same trend as shown in the previous figure can be observed, if the pitch angle is switched with the flying height. Figure 12 shows the flying height of the Femto slider at different radial positions with and without the van der Waals force. The van der Waals force changes the flying height significantly, especially at the inner radius. It lowers the flying height from 4.14 nm to 3.14 nm at the inner radius, but only lowers it from 1.65 nm to 1.54 nm at the outer radius. This seems unusual, since at the outer radius the slider flies at lower flying height, so the van der Waals force should have a larger effect. But this particular design has a relatively large pad at the trailing edge, so its van der Waals force is more sensitive to the pitch angle than is the case for the Tripad slider, which has a small and short pad at the trailing edge. It is not difficult to understand that the lower flying height and smaller pitch angle make the van der Waals force stronger, since more material of the slider is brought closer to the disk surface. The Femto slider has a pitch angle of 326.1 $mrad$ at the outer radius versus a 142.4 $mrad$ pitch angle at the inner radius. This is shown in the Fig. 13. The much larger pitch angle effect surpasses the lower flying height effect at the outer radius, and the net result is a smaller van der Waals force effect on the flying height at the outer radius. Figure 13 also shows that the van der Waals force slightly increases the pitch angle at the inner radius. Figure 14 shows that the van der Waals force does not influence the roll angle very much.

Figure 15 shows the effect of the repulsive portion of the intermolecular force on the total force for the Tripad slider at a fixed pitch angle of $150 mrad$. At a flying height of about 0.35 nm, which is the place where the repulsive intermolecular force becomes non-negligible, both the total intermolecular force curve and the total force curve start to deviate from their counterparts with only the pure van der Waals force included. They increase rapidly and become positive (repulsive) after a minimum negative value has been reached, instead of continuing to decrease rapidly as was the case with only the van der Waals force included. Figure 16 shows the same trend for the Femto slider. This indicates that for sliders with a steady state flying height below 0.4~0.5 nm or having intermittent contact or near contact dynamic performance, the repulsive intermolecular force needs to be included.

CONCLUSIONS

The intermolecular forces have been incorporated into a steady state air bearing design code. Simulation results for two typical slider designs show that the van der Waals force has a significant effect on the total load capacity and flying height of both the positive and negative pressure sliders , when the sliders fly below 5 nm. It significantly lowers the flying height and slightly increases the pitch angle, but it has negligible effect on the roll angle. For sliders with relatively large rear pads, the van der Waals force effect is also sensitive to the pitch angle change, and it must be accounted for in the design code before an accurate flying attitude of the slider can be obtained. The results presented here also demonstrated the same phenomenon observed by other investigators, that the van der Waals force results in a lower limit clearance below which the slider can not sustain any load. This is totally different from the cases where the van der Waals force is not included. Our results also show that the repulsive portion of the intermolecular force needs to be included when the flying height is below 0.4~0.5 nm.

ACKNOWLEDGEMENT

This work was supported by the Computer Mechanics Laboratory at University of California at Berkeley and a grant from the National Storage Industry Consortium.

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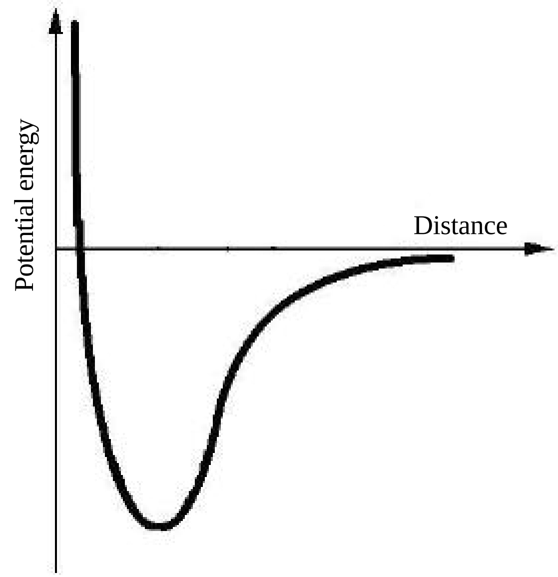

Fig. 1 The potential energy between two molecules.

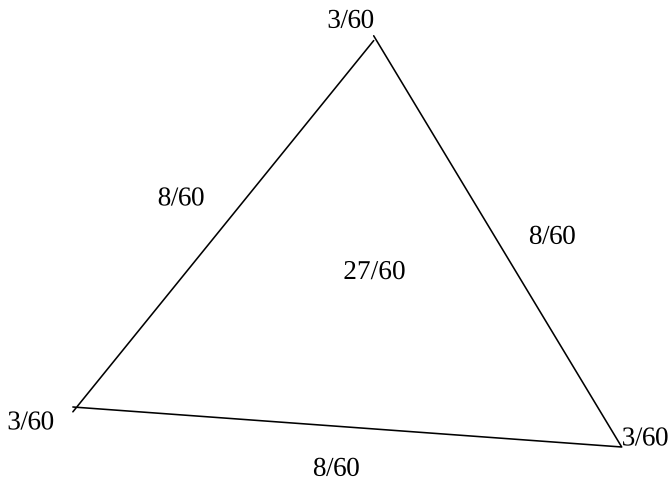

Fig. 2 The constants used in the 7 point quadrature.

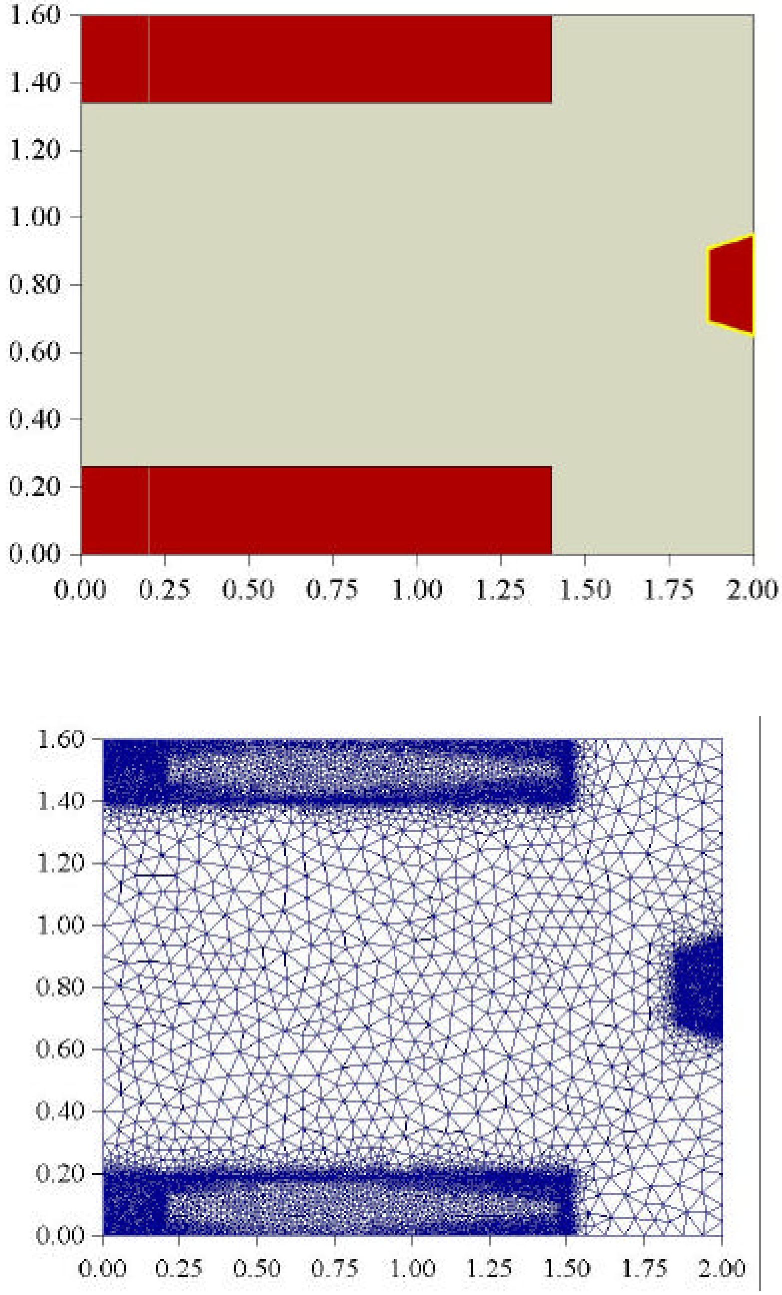

Fig. 3 The Tripad positive pressure slider and the unstructured triangular meshes.

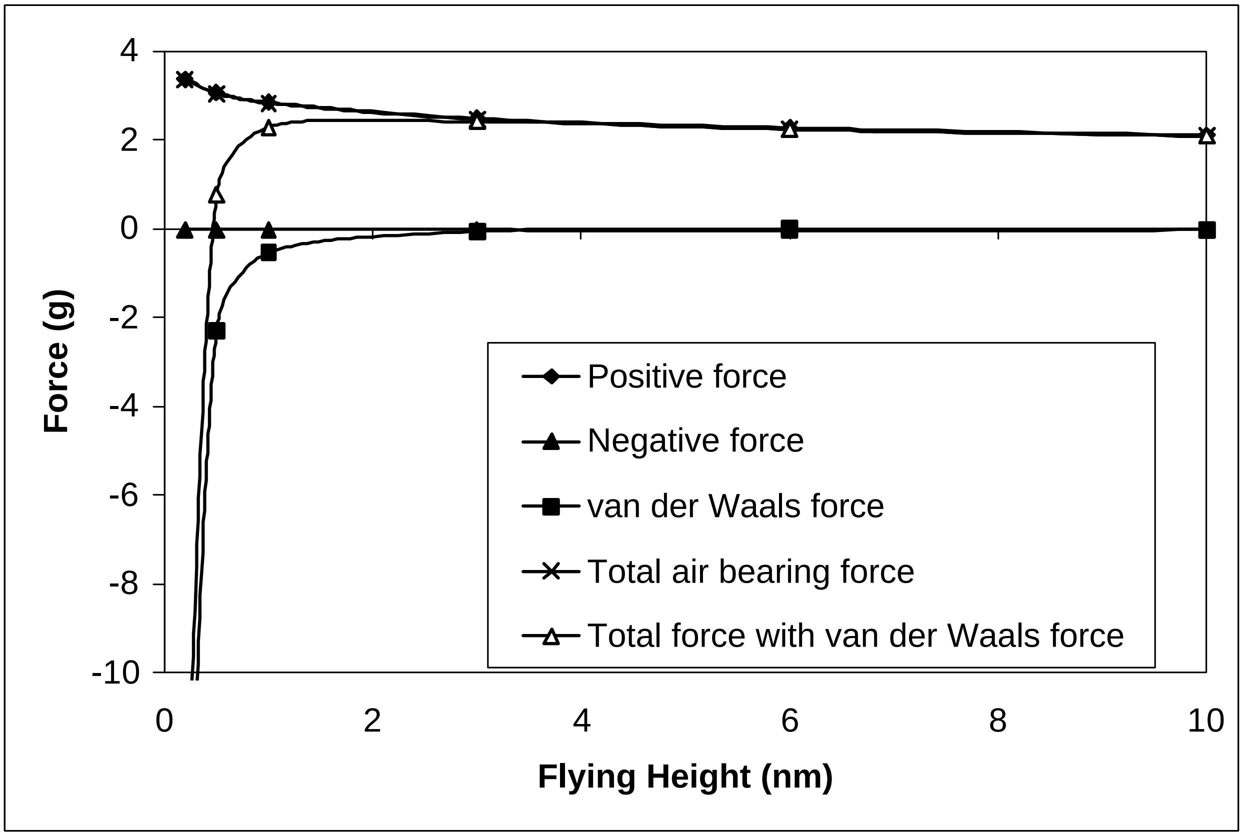

Fig. 4 Air bearing forces, the van der Waals force and the load capacity as a function of the flying height for the Tripad slider at a fixed pitch angle of $150 mrad$.

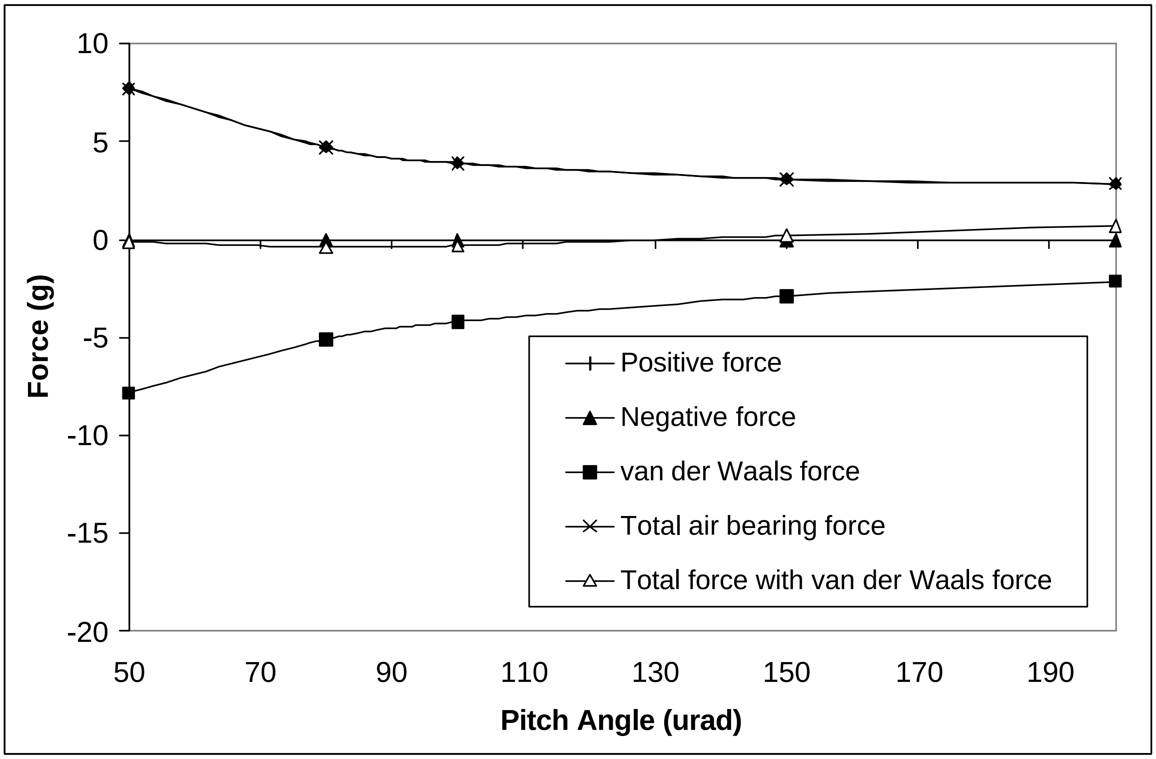

Fig. 5 Air bearing forces, the van der Waals force and the load capacity as a function of the pitch angle for the Tripad slider at a fixed flying height of 0.45 nm.

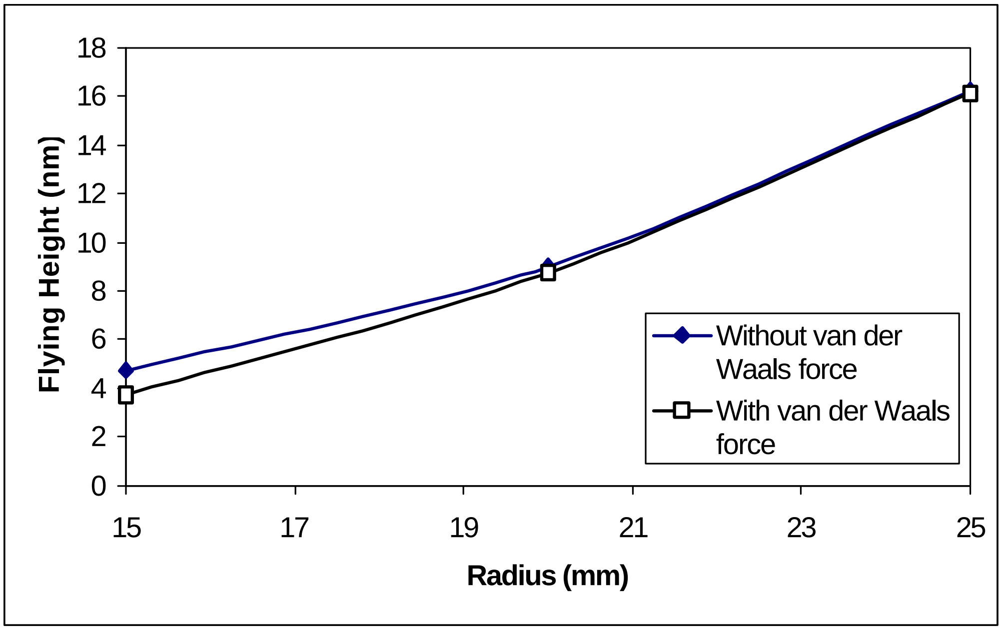

Fig. 6 The effect of the van der Waals force on the flying height of the Tripad slider at different radial positions.

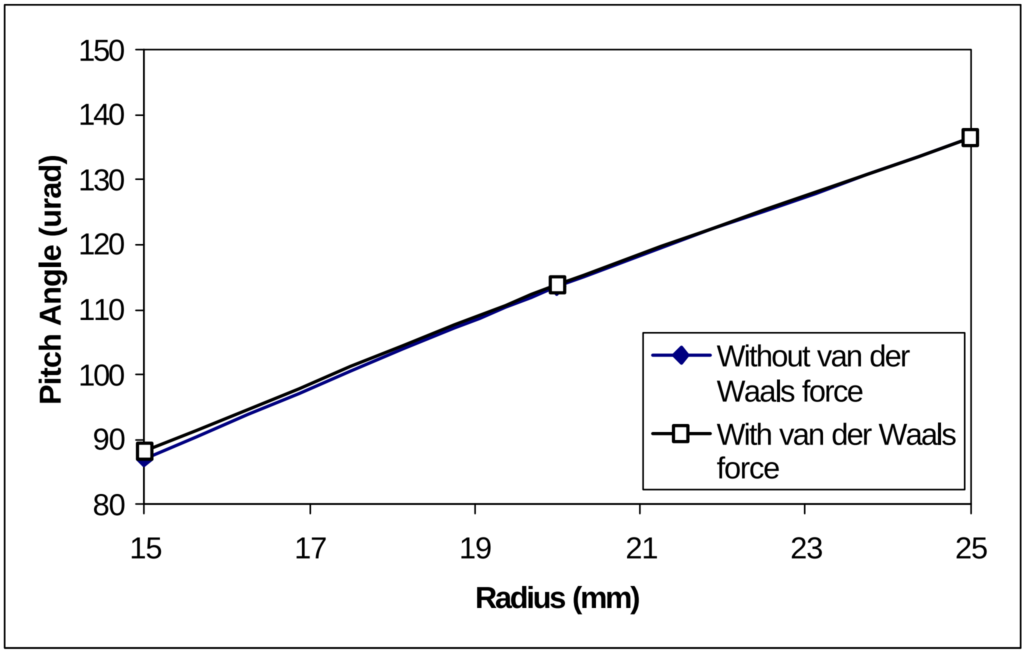

Fig. 7 The effect of the van der Waals force on the pitch angle of the Tripad slider at different radial positions.

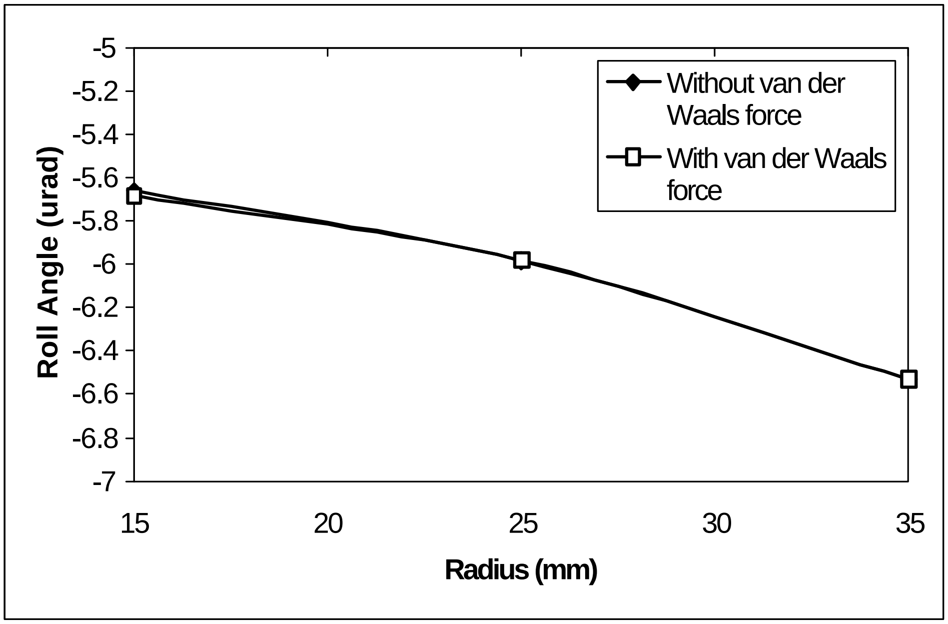

Fig. 8 The effect of the van der Waals force on the roll angle of the Tripad slider at different radial positions.

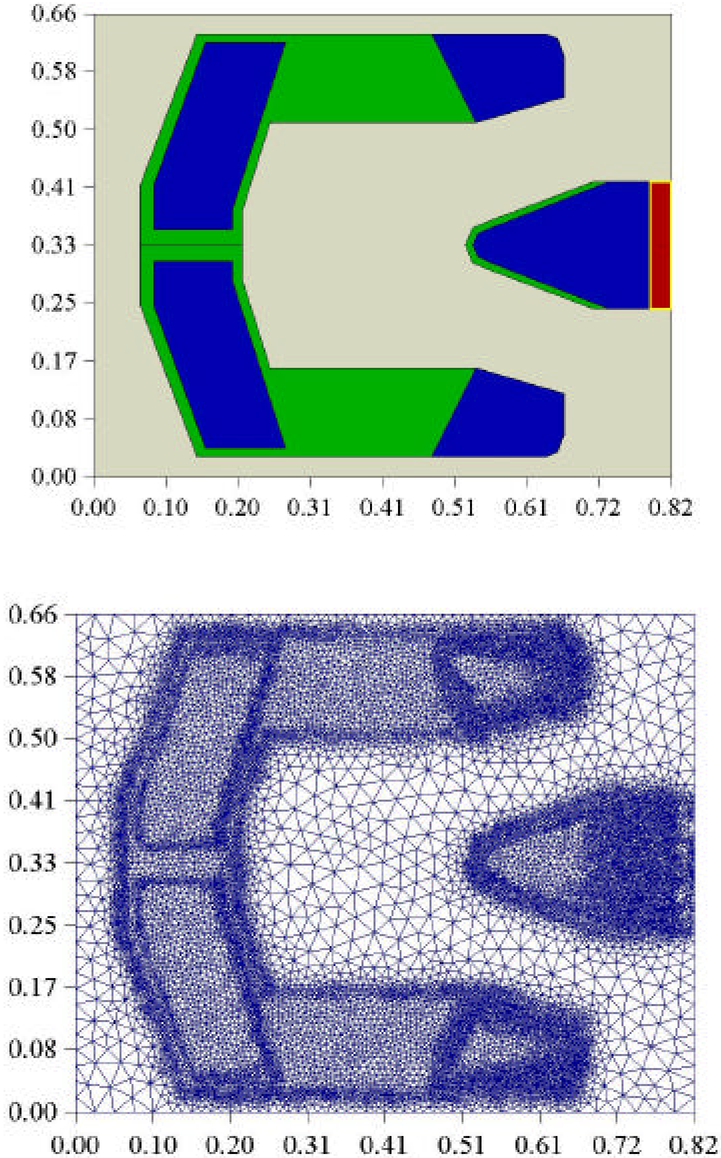

Fig. 9 The Femto negative pressure slider and the unstructured triangular meshes.

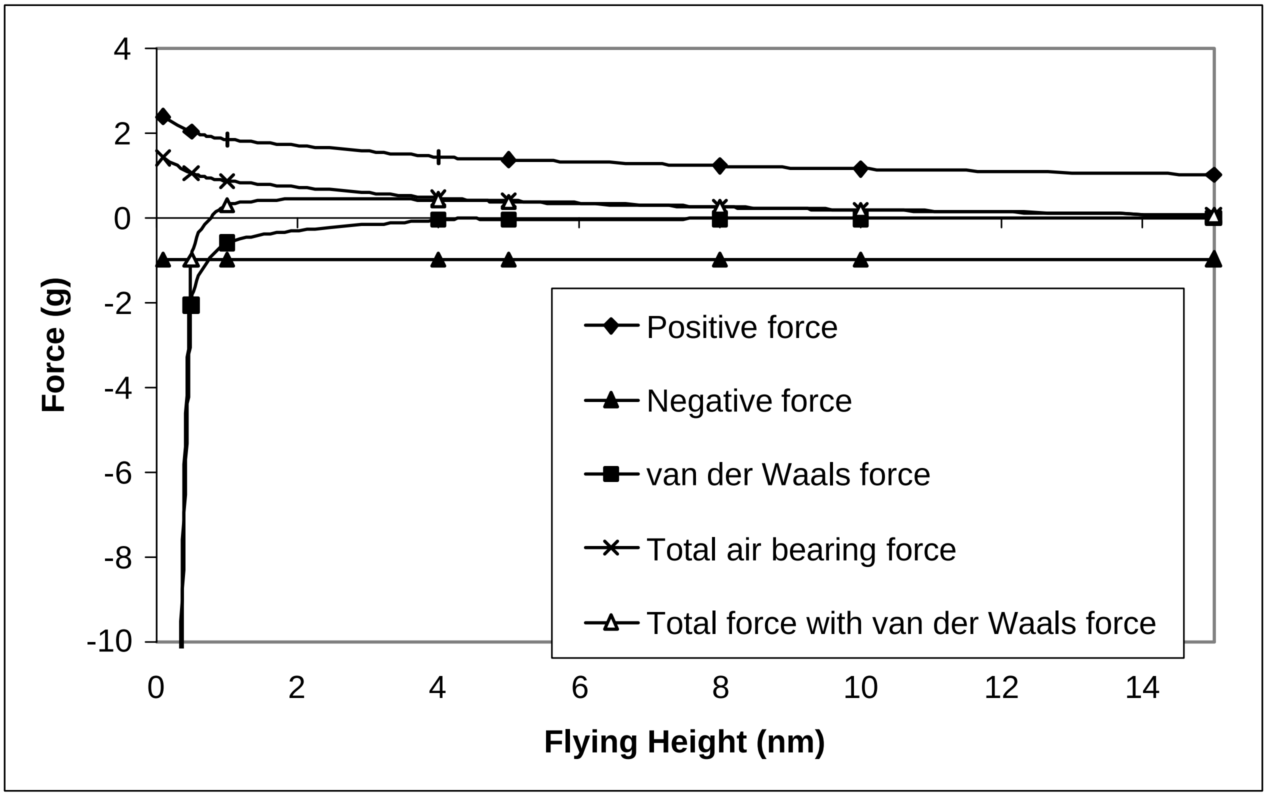

Fig. 10 Air bearing forces, the van der Waals force and the load capacity as a function of the flying height for the Femto slider at a fixed pitch angle of $150mrad$.

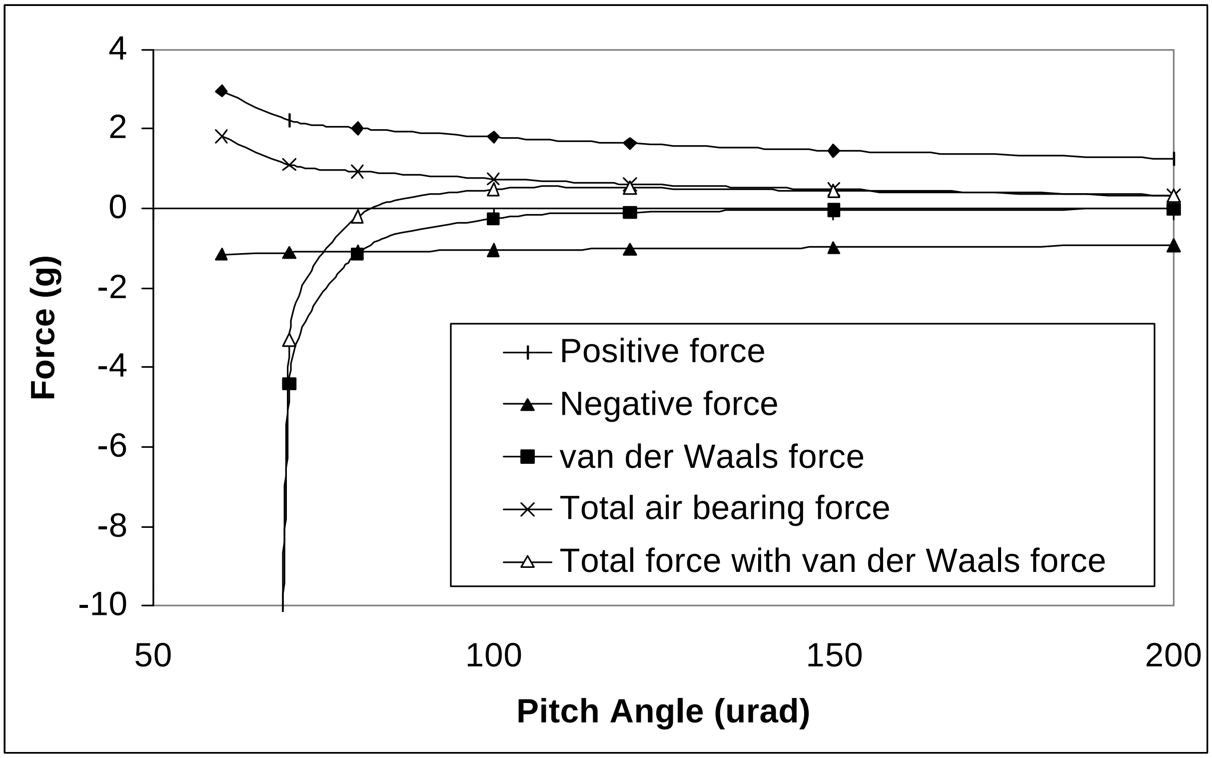

Fig. 11 Air bearing forces, the van der Waals force and the load capacity as a function of the pitch angle for the Femto slider at a fixed flying height of 4 nm.

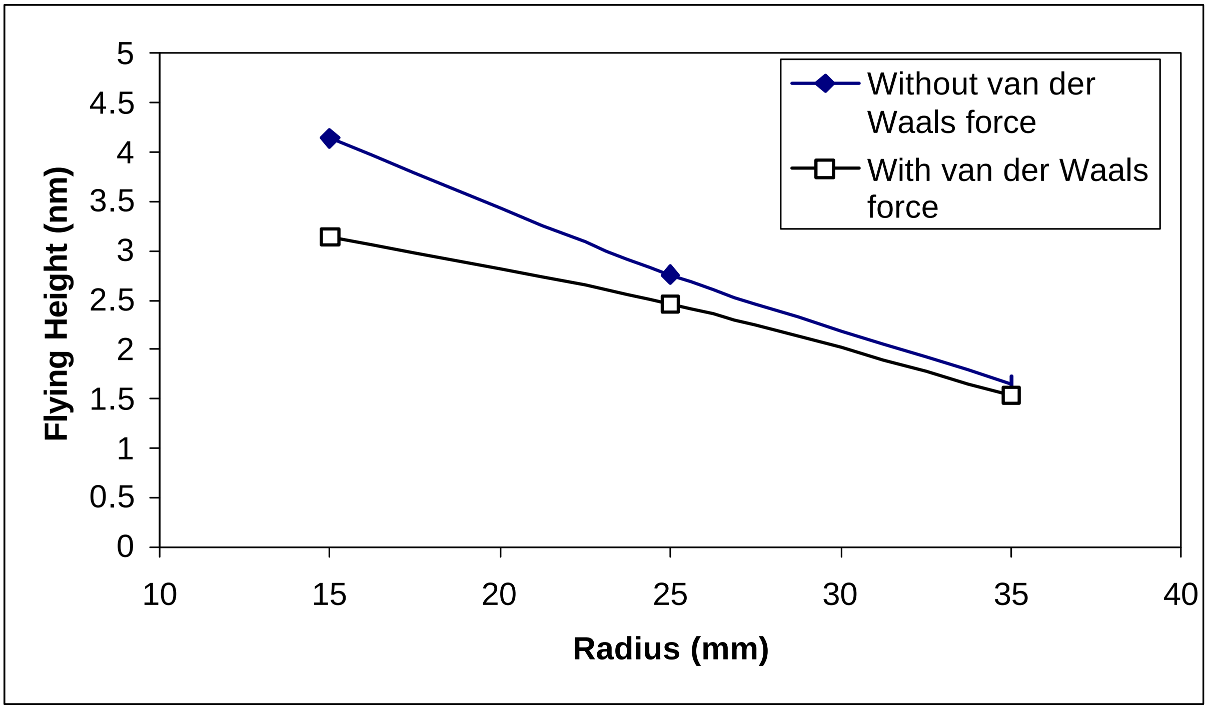

Fig. 12 The effect of the van der Waals force on the flying height of the Femto slider at different radial positions.

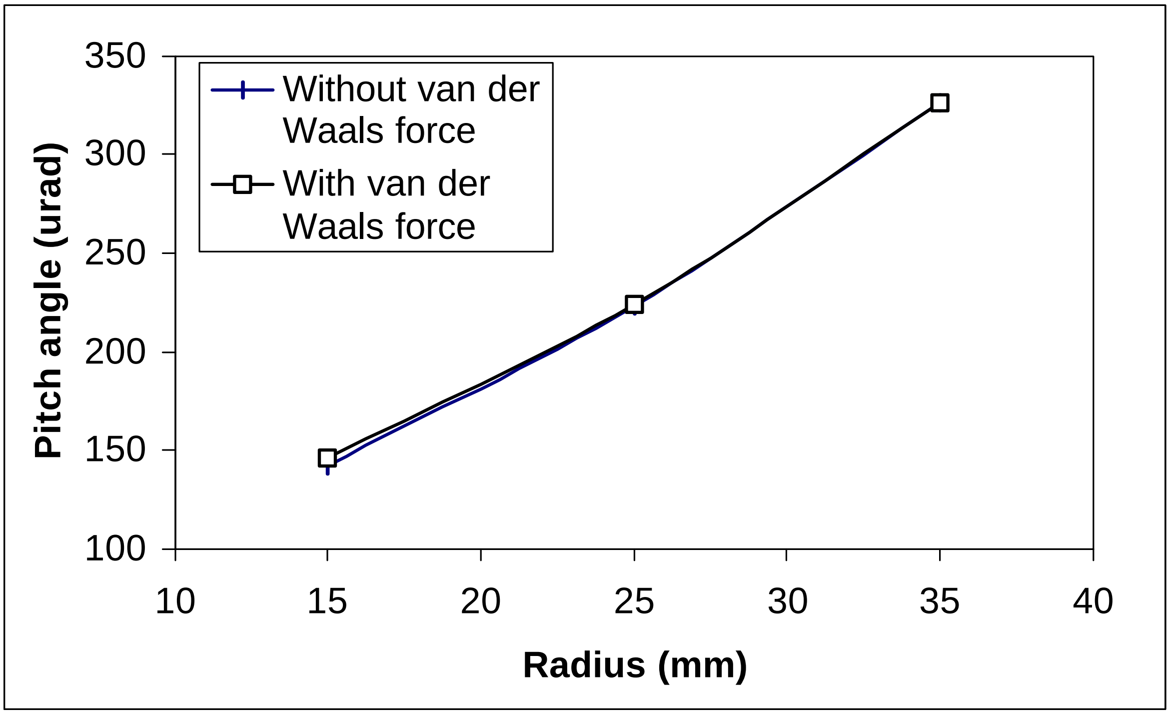

Fig. 13 The effect of the van der Waals force on the pitch angle of the Femto slider at different radial positions.

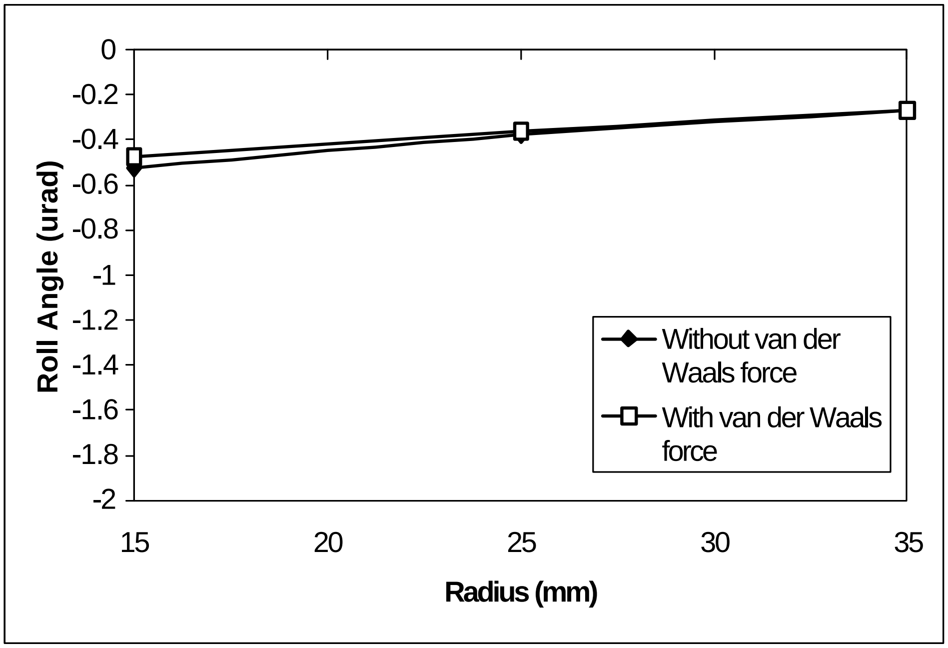

Fig. 14 The effect of the van der Waals force on the roll angle of the Femto slider at different radial positions.

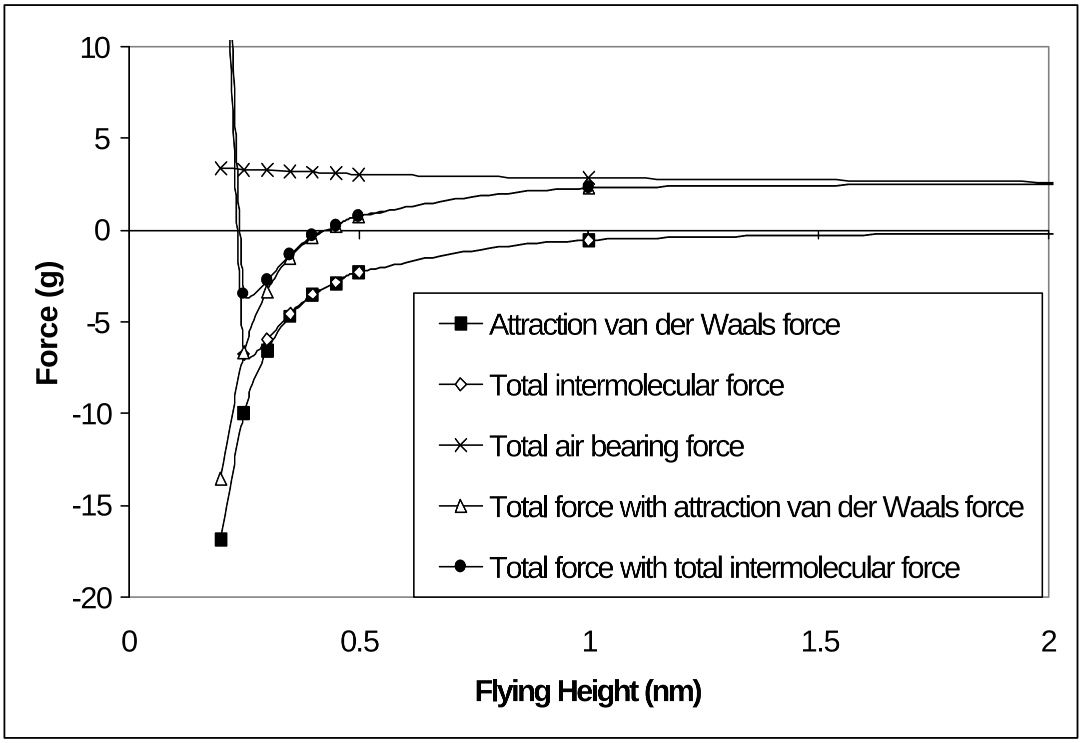

Fig. 15 The attraction van der Waals force, the total intermolecular force, the total air bearing force and the load capacity as a function of the flying height for the Tripad slider at a fixed pitch angle of $150 mrad$ **.**

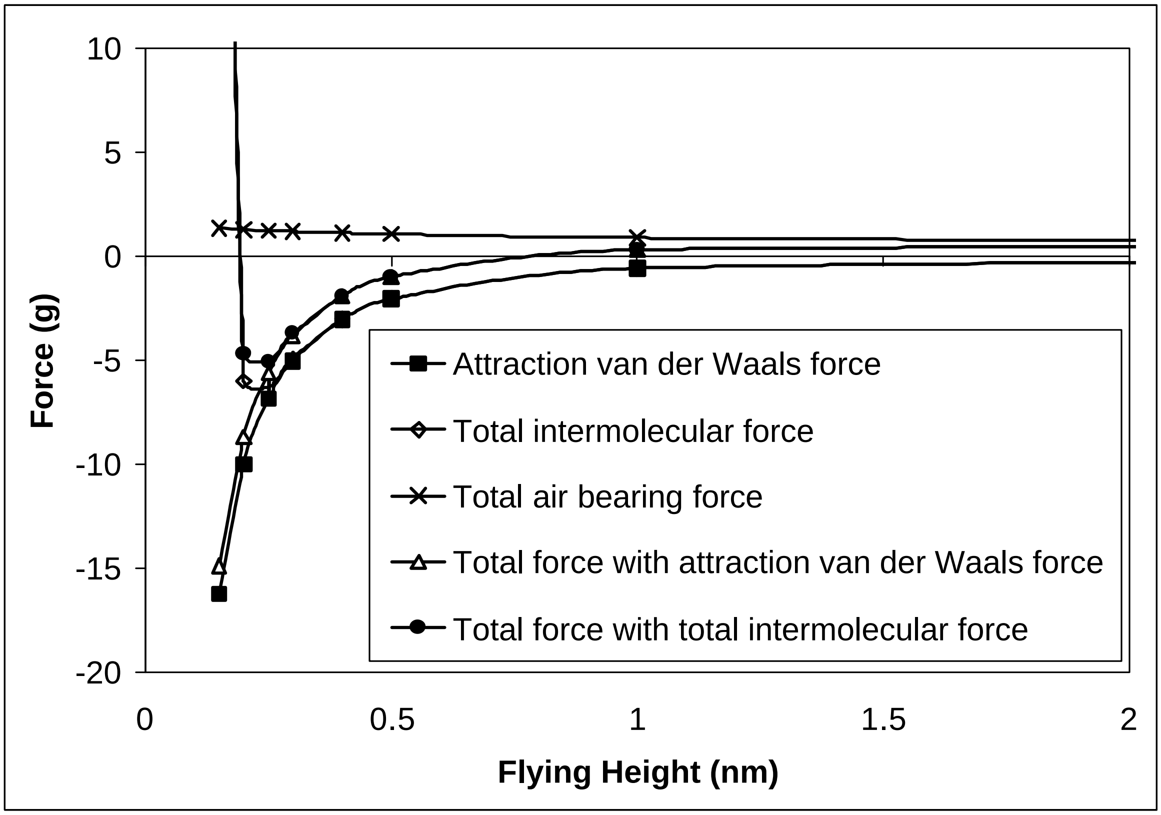

Fig. 16 The attraction van der Waals force, the total intermolecular force, the total air bearing force and the load capacity as a function of the flying height for the Femto slider at a fixed pitch angle of $150 mrad$ **.**