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Non-contact handling in microassembly: Acoustical levitation

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Abstract

Microassembly is currently of the utmost importance in industry. Nevertheless, the classical assembly processes are no longer usable for very small components, typically ranging from 10 μm to 10 mm, since usually neglected surface forces disturb the handling task by inducing adhesion between the component and the gripper. A promising alternative to tackle surface forces consists in levitating the handled component. The various advantages of this contactless handling method are reviewed here and justify the choice of this approach. Consequently, the numerous physical principles suitable for contactless handling are briefly described together with their limitations. The evaluation shows that acoustic levitation is best fitted in the case of microassembly. A classification of literature applications is presented hereafter with special focus on acoustic levitation. Finally, the most common models of acoustical levitation are inspected in a general way. The described models come within the scope of non-linear acoustics.

Keywords: Microassembly; Levitation; Contactless; Ultrasonic; Acoustical; Handling

1. Introduction

A large number of industrial developments are currently made with regard to microproducts since miniaturization is of crucial importance. Starting from successes achieved in microelectronics and especially MEMS, hybrid mechanical and opto-electronic microsystems are currently developed. As opposed to the monolithic systems used in semiconductor technology, the functionalities result from the combination of single components which must be integrated through microassembly processes [1]. When the size of the part decreases, microassembly becomes the most expensive task, owing to the difficulties of automation [2].

Several definitions can be found in literature to characterize *micro*components. In this work, we adopt the definition used in assembly: components whose handling is disturbed by the surface forces are all included in the microscale whatever the size they may have, even if experiments and models show a typical boundary of about 1 mm.

In assembly dealing with microcomponents, usually neglected forces (electrostatic, van der Waals, surface tension forces) become dominating. For macromanipulation, the main challenge lies in picking objects and then developing sufficiently stiff tools to tackle the effects of gravity and inertial forces. At the microscale, gravity and inertial forces are not so significant compared to surface forces, and releasing an object becomes a real challenge due to the adhesion between object and tool. A promising alternative consists in avoiding adhesion by levitating the handled component.

In the present section, we point out the importance of microassembly in the current industry and the needs for improvement in the techniques used nowadays. The concept of surface forces is then introduced, and the perturbation they can induce on the microassembly task is briefly explained. Four strategies found in literature to tackle the effects of surface forces are then exposed in Section 2. Avoiding the contact seems to be the most appropriate method for microassembly processes, and the various advantages of the non-contact technique are reviewed in Section 3. Section 4 deals with the numerous physical principles suitable for contactless handling. A comparison table justifies the choice of the acoustic levitation. A classification of the existing applications is presented in Section 5, and some conclusions are

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drawn concerning the acoustic levitation variants. The numerous models previously developed by authors on acoustic levitation are then inspected in Section 6, and various assumptions and limitations are pointed out. The last section of this work gives some conclusions and future prospects.

2. Surface forces

Surface forces can lead to release problems when handling microcomponents [3–5]. Much more information can be found in [6–8].

These effects have also been experimented by a lot of industrials involved in the handling of small components, as for example MEMS, mobile phone components (Nokia), household appliance components (Zanussi, Philips), or the watchmaking industry (Swatch) [9].

In order to improve micropart manipulation, four main strategies have been set up to tackle these surface forces; they are summarized in Fig. 1.

Firstly, the effects of surface forces can be reduced by choosing an adapted set of manipulation parameters. This can for example be done by changing the coating. Surface tension effects can be reduced with hydrophobic coatings [10], electrostatic forces by using conductive materials [3] or van der Waals forces by increasing the roughness profile [3,11–14]. Unfortunately, this approach is still *macro* thinking driven and is neither sufficient nor possible in all cases.

Consequently, a second approach can be followed consisting in overcoming the surface forces during the release task, such as for example by glueing the component at the right place [15], using dynamic release [16], using a smaller auxiliary tool [11], blowing away the handled component [17].

The third way to tackle this problem consists in taking advantage of the adhesion effect to set up new handling principles. Several examples are given in literature, such as the gripping based on the surface tension effects [18,19], the electrostatic handling [20,21] or the handling using van der Waals forces [11,22]. Further information on these gripping principles can be found in [23,24]. Nevertheless, the adhesion effects are still present during the release task and special attention has to be paid to the latter.

Finally, some unavoidable difficulties due to the surface forces lead to a fourth approach: if the gap between the component and the gripper can always remain larger than the cut-off lengths of the physical principles leading to adhesion, the handling task can be performed without paying attention to the surface forces. Typically, this cut-off length is about 100 nm for van der Waals forces [5].

It means that the manipulation has to be performed without any mechanical contact and inherently avoids any effect of the surface forces. This last approach will be described in details within the scope of the present paper.

3. Advantages of non-contact handling

The advantages of this contactless handling approach can be summarized as follows. Some of the advantages listed are not limited to the handling of microcomponents.

- As explained above, surface forces can be completely neglected.
- The friction effect is drastically reduced, which enables high resolution and accuracy motion devices by avoiding the stick-slip effects [25].
- Handling of tricky (fragile, freshly painted, sensitive or micron-sized structured surfaces) components is feasible because high local contact pressure by direct mechanical contact is avoided [26]. Handling of non-rigid products is also possible due to the force field [27].
- Contamination from and of the end-effector can be totally avoided. This can be important in food handling [27] or in presence of lubricant [28].
- In material science, measurements of some physical properties are allowed on very small liquid or solid samples avoiding undesired contamination from the container and eliminating wall-driven heterogeneous nucleation [29].

In microassembly, the handling of fragile and surface sensitive components of microsystem technologies represents a great challenge. Processes used in classical assembly tend to be based on the mechanical contact, which may result in the destruction of fragile parts. It thus makes sense to manipulate such parts without any physical contact.

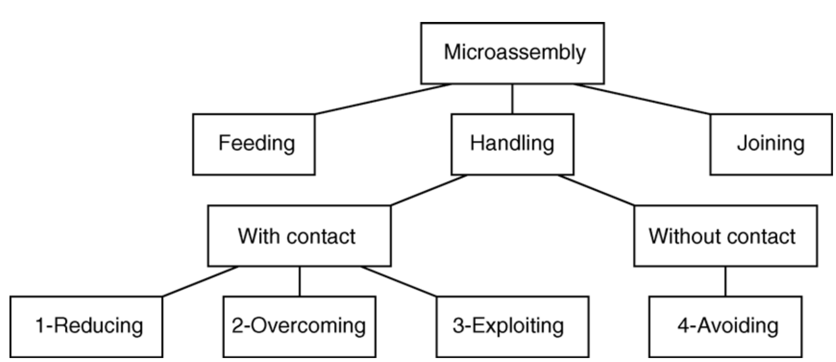

Fig. 1. Four strategies as far as the surface forces are concerned.

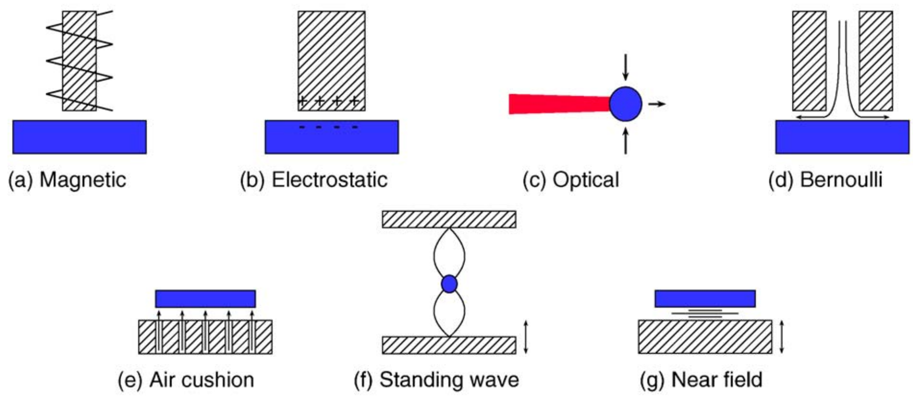

Fig. 2. Some levitation principles.

4. Principles suitable for contactless handling

In this section, some physical principles used for non-contact manipulation are succinctly described. The advantages and drawbacks of every principle are then inspected in a general way. For more detailed information, see [30].

4.1. Levitation techniques

The literature review highlights five distinct techniques: they are mainly magnetic, electric, optical, aerodynamic and acoustic levitation. These classes are split into several variants; some of the most common ones are shown in Fig. 2.

Once the object is levitated, it must be laterally moved in order to perform the manipulation task. Non-contact lateral propulsion is based on the same physical principles as non-contact levitation. Other variants are specially designed for propulsion, but we confine ourselves to levitation in the following. The same principle can be used for both levitation and propulsion or, on the other side, physical principles can be mixed. Another way of manipulating a component lies in moving the whole levitation system. The control of the levitation parameters should also give an additional degree of freedom in the handling of the component by varying the levitation height.

4.1.1. Magnetic

The levitation force comes from a magnetic field generated by magnets (Fig. 2a). Three different types can be used: permanent magnets, electromagnets or superconducting magnets. The use of electromagnetic levitation is limited to materials with high electrical conductivity and to low-temperature applications [25,28,31].

There are mainly two types of magnetic levitation. The first one refers to the electromagnetic system (EMS) while the second one is called electrodynamic system (EDS) [32,33].

In the electromagnetic system, an attractive force is generated between normal electromagnets and a ferromagnetic guide. The equilibrium position is unstable and a feedback control loop must be applied to the system to ensure stability [25,32].

Electrodynamic levitation is based on the induction of eddy currents in conducting materials. These eddy currents can be induced by a time varying magnetic field [34]. A first kind of electrodynamic system is based on the force acting between the magnetic field generated by superconducting magnets and the stationary coils located in the guideway. The variation of the field is induced by the relative motion between the superconducting magnets and the stationary coils [32]. Another variant of electrodynamic system is based on the force generated by a time varying current inducing magnetic field variations [34]. This kind of electrodynamic levitation is sometimes classified in electric levitation as seen below. The forces are repulsive and this levitation mechanism is passively stable.

Moreover, some hybrid or synthesis systems are found [32,35]. Systems using permanent magnets are always hybrid because the levitation with forces only coming from permanent magnets is never totally stable in all degrees of freedom.

4.1.2. Electric

This technique can be used to directly manipulate several kinds of particles such as conductive, semiconductive and dielectric materials (Fig. 2b). A distinction can be made between electrostatic and electrodynamic levitation.

In electrostatic levitation, static electrical fields can be used to attract and orientate microcomponents. Both conductive and dielectric objects are attracted towards regions with a higher electric field [2]. This technique can also be used

Fig. 3. Force components for a weakly converging laser beam.

to levitate small uncharged particles by induced polarization of the sample. Attractive forces make the use of closed-loop control necessary to ensure stability. Moreover, the suitability of electrostatic levitation is proved only for low temperature fields. At high temperature the static charges are not maintained and they are gradually degenerating in course of time. On the other hand, relatively large particles can be levitated [36].

The electrodynamic principle is often referred to as the pico-balance. Charged particles are held stationary using a combination of static (DC) and oscillating (AC) electric fields. If correctly applied, the oscillating component will provide stabilizing forces to the particle [37]. This technique is able to suspend and levitate a small charged particle. The disadvantages lie in the poor particle stability and in the limited particle size (up to 200 μm) [37].

4.1.3. Optical

Optical levitation was first discovered by Ashkin [38]. Particles can be freely suspended and accelerated by the forces of radiation pressure from visible laser light (Fig. 2c). Stable potential wells exist where particles can be trapped.

The main problem rests on the obscuring effects of thermal forces caused by temperature gradients induced in the medium surrounding the object. These forces are generally named radiometric forces and more precisely photophoresis effect as far as light is concerned. These thermal forces make the levitation positions unstable and can be avoided by suspending relatively transparent particles in transparent surrounding media (water, oil, air . . .).

Due to both beam reflection and refraction, the particle undergoes two force components as represented in Fig. 3. The so-called [39] scattering force is proportional to the optical intensity and points in the direction of the incident beam, while the gradient force is proportional to the intensity gradient and points in the positive intensity gradient direction when the refractive index of the scatterer is greater than that of the surrounding medium. If the relative magnitude of the indices is reversed, the sign of the radial force is changed and the sphere is pushed out of the beam [38–40].

A wide variety of optical traps have been proposed on the basis of scattering and gradient forces. When using a weakly converging single laser beam, the particle is confined to the beam centre but propelled along the beam. Axial stability relies on the balance of scattering force and gravity [41]. Another kind of laser beam trap consists in a highly convergent beam and is commonly called *optical tweezer*. The axial gradient force dominates the axial stability and the particles are trapped near the beam focus [41,42]. Other trapping methods use two or several laser beams to generate only one stable equilibrium point located below the beam-crossing point [43].

Note that this principle leads to a gripping force that hardly reaches 1 nN [23], which represents the weight of a 32 μm edge cube with a density of 3 kg/dm^3.

4.1.4. Aerodynamic

Aerodynamic levitation uses a flow of gas or liquid to apply a force. According to the flow direction, two different approaches can be considered: air cushion or Bernoulli levitation.

In Bernoulli levitation, the sample is held below the end-effector of the manipulator which consists in a radial air outflow nozzle (Fig. 2d). Compressed air from a high pressure supply flows downwards through the nozzle and, after having struck the component, flows radially outwards. If the clearance gap between the nozzle head and the component is small, the radial flow velocity increase induced by the section reduction leads to a dynamic pressure decrease by Bernoulli effect, resulting in an upward attracting force on the component. When the gap becomes too large, repelling forces appear and the component is blown away. When the gap becomes too small, the air cannot flow any more and the attracting force is reduced. The component thus reaches a stable position under the manipulator [27,44,45].

In air cushion levitation, the sample is held above the manipulator (Fig. 2e). Pressurized air flows upwards through several holes which are drilled all over the gripper and leads to a repulsive levitation force that counterbalances the weight of the component [46].

Other hybrid variants of aerodynamic levitation use both previous principles. Manipulators using simultaneously an upward suction force and a downward air cushion are found in literature [44].

4.1.5. Ultrasonic acoustical

The last principle uses acoustic waves to apply forces on the part to be manipulated. Two configurations can be found in literature: standing wave levitation and near-field levitation [47].

In standing wave levitation, small components can be levitated in the pressure nodes of an acoustical standing wave between a vibrating plate and a reflector (Fig. 2f), while in squeeze film levitation the reflector is replaced by the levitated object itself (Fig. 2g) [26].

Acoustic standing wave levitators, often referred to in technical literature as *single axis, open acoustic positioners*, offer forces which are capable of balancing particles with weights of the order of a few grams in a gaseous atmosphere and under terrestrial conditions. This range can be widely extended if performed under microgravity conditions or in a liquid environment [36].

A schematic ultrasonic levitator is shown in Fig. 4 with the distribution of the acoustic pressure, acoustic velocity and the axial levitation force in a standing plane acoustic wave. To generate the standing wave, the vibrator is placed at a fixed distance from the reflector, which ideally is a multiple of half the wavelength ($n\frac{\lambda}{2}$). Under microgravity conditions, a particle would be positioned exactly in the pressure node (point of zero acoustic pressure). Since the acoustic velocity and pressure are shifted by 90° in order to satisfy the Bernoulli equation, a pressure node may also be referred to as veloc-

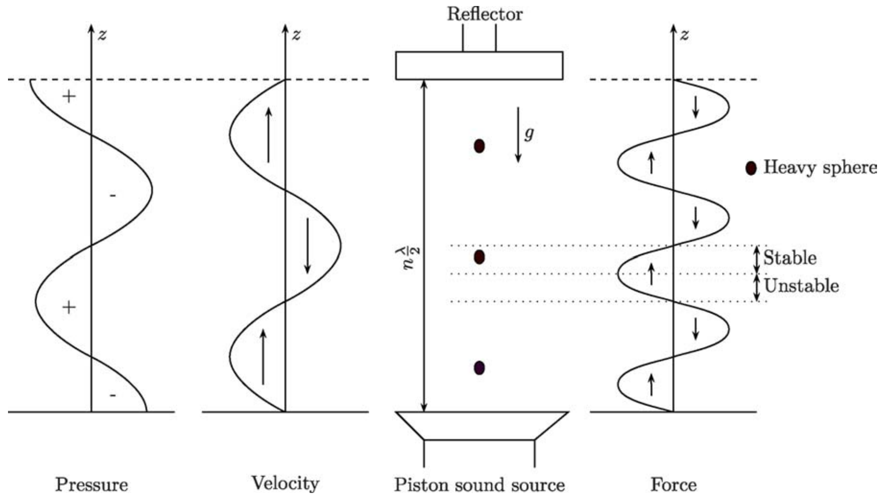

Fig. 4. Levitation of dense spheres in an acoustic standing wave [36].

ity loop (point of maximum velocity) or velocity anti-node [36].

At pressure nodes, the levitation force is zero while everywhere else levitation forces act in the direction of the nearest pressure node. In a terrestrial environment, suspended particles will be positioned below the pressure node and stabilized by the levitation force originating in the anti-symmetric part of the acoustic radiation pressure. Depending on the chosen node, stable levitation can occur with an axially upward or downward flow, which can be useful in some experiments.

Moreover, centring of the part along the centre axis of the levitator is accomplished on the basis of the non-ideal acoustic field. An acoustic wave is never perfectly plane, but is always somewhat divergent. The static pressure distribution of the standing wave generates a high frequency flow around the part, the speed of which decreases towards the periphery. The Bernoulli vacuum pressure generated with radial deflections pulls the part back to the centre axis. With appropriate optimization of the transmitting transducer, the radial positioning forces may easily reach up to 30% of the axial levitation force [1].

It is not compulsory to operate the levitator in an upright position as seen in Fig. 5a. Thanks to the radial positioning force F_r, the levitator can be tilted or even turned in the horizontal plane, serving as an acoustic microgripper. In this connection, it should be mentioned that the reflector axis does not have to be aligned with the vibrator axis as seen in Fig. 5b. Possible angles between the axes of the sound transmitter and reflector of up to 60° were successfully tested [48]. These two last properties offer a lot of gripping capabilities in microassembly.

In order to achieve precise positioning, several methods can be applied to an ultrasonic standing wave levitator. Some of them allow the transportation of suspended particles by changing node positions without varying mechanical parameters. One can for example use a fixed frequency difference introduced between two opposite transducers [49]. Other methods use mechanical parameters because translational or rotational movements of the part within the gripper can be performed by moving the reflector in axial or radial directions [48].

Another approach of using high intensity ultrasonics for non-contact handling consists in levitating planar objects slightly above the manipulator surface with a high intensity vibrator. This technique is called near-field levitation and is often referred to by several authors as squeeze film levitation [1]. The part is lifted through direct radiation of the underside within the near field of a high intensity ultrasonic transducer. The load carrying gas film is created by rapid vibrations of the manipulator [50]. Not only in-phase longitudinal mode, like piston motion, but also flexural vibration mode can be employed as radiation sources [51–54].

The achievable levitation heights are normally quite small depending on the intensity of the sound transducer. As opposed to standing wave levitation, considerable forces can be applied to the parts. Consequently, any weight can be levitated if the separating distance between the object and the vibrating plate is small enough [1,55].

Centring forces using near-field levitation can be effected in various ways. The vibrators can be set up in an oblique position or the levitation force can be varied in order to create a potential well where the parts automatically return because of gravity. The vibrator shape or the vibration mode can be

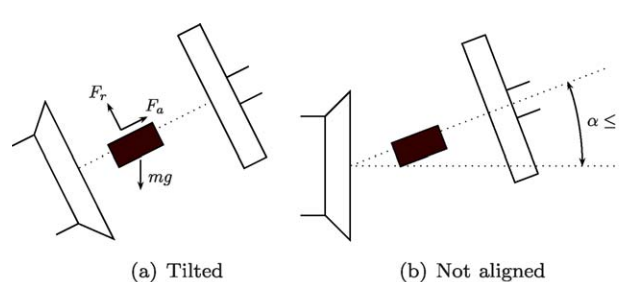

Fig. 5. Useful features for microgripping.

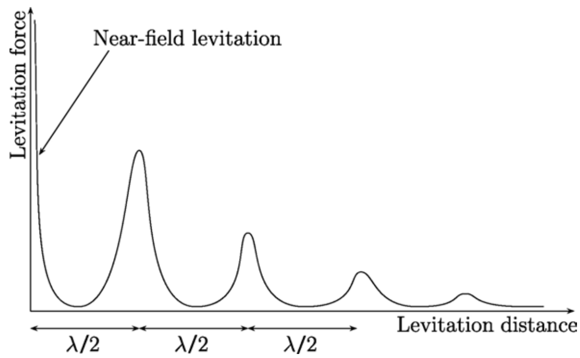

Fig. 6. Levitation force as a function of levitation distance [48].

tuned to naturally induce centripetal viscous forces which work against lateral sliding of the lifted part [1,55].

Finally, planar parts can be levitated above an ultrasonic vibrator at intervals of half the standing wave length. The resultant standing wave patterns balance the part which acts as a reflector. The typical levitation force profile is shown in Fig. 6 as a function of the levitation distance [48].

Clearly visible on this graph is the steeply rising levitation force in the near-field, behaving inversely proportional to the square of the levitation distance. At intervals of half the wavelength, there are additional force peaks where objects can be suspended. However, the force achievable in this way shortly decreases with increasing distance.

At the present time, it appears that acoustic levitation is the most suitable method for a wide range of applications. The main advantage of acoustic processing lies in the fact that any material, insulator or conductor, magnetic or non-magnetic, can be manipulated by acoustic forces [56]. Simple bulk parameters, like density or sound velocity, scale the forces, but a stable equilibrium position always exists, when supplied with sufficient sound power. Nevertheless, surface properties, like roughness, can influence the fluid flow around the part and slightly modify the acoustic field. The primary disadvantages of acoustic levitation are acoustic streaming and non-uniformity of the force field. The energy density distribution induces an acoustic convection flow. This streaming effect enhances heat and mass transfers, which can be an advantage in chemistry experiments as well as a drawback in positioning. Slight unsymmetries in the acoustically induced convective flow field result in mostly undesired and uncontrolled sample rotations.

4.2. Comparison of the principles

The various levitation principles have been extensively evaluated with several criteria for their suitability in microassembly. The following aspects have been taken into consideration:

- handled objects shape and size restrictions,
- material type limitations,
- maximum generated levitation force,

Table 1
Comparison of the different principles for use in non-contact handling

Principle	Object shape and size	Material limitation	Maximum levitation force	Stability
Electromagnetic	None	Restricted to conductive materials	Not limited	Unstable without control loop
Electrodynamic	No microelectronic components	Restricted to conductive materials	Not limited	Stable
Electrostatic	–	Force depends on the material type; better control with conductive materials	Not limited	Unstable without control loop; disturbing forces induced by tribo-electrification
Optical	Small spheres up to 50 μm in diameter	Higher refractive index than that of the surrounding medium; dielectric; relatively transparent	0.1–1 nN	Stability conditioned by the refractive index ratio; oscillations better damped in liquids; instabilities due to thermal effects involving flow in the surrounding medium
Bernoulli	Parts with one flat surface at least	Not too compliant; not too porous	–	Lateral stability despite a rocking motion (plate does not remain parallel to the nozzle surface)
Air cushion	Planar parts	None	0.1–10 N	Horizontal instabilities due to the absence of centring effect
Standing wave	Various shape; size smaller than one eighth of the wavelength	None	10 mN	Axial stabilization; natural centring effect by Bernoulli effect; orientation controlled by unsymmetries in the field; acoustic streaming leads to a destabilizing force
Near-field	Planar parts; preferably thin plates	None	Not limited	Centring effect achieved by tuning the vibration mode

Table 2
Comparison of the different principles for use in non-contact handling (continued)

Principle	Environment limitation and interaction	Complexity and compactness	Microhandling capabilities
Electromagnetic	Restricted to low temperature applications; neighbouring processes perturbed by high magnetic field	Large bulk and mass of the electromagnet; need for shielding	Handling of non-conductive parts by attaching a metallic device to it (mechanical contact)
Electrodynamic	Restricted to low temperature applications; neighbouring processes perturbed or damaged by high magnetic field and eddy currents	Need for liquid nitrogen to cool the superconducting magnets (when used); need for shielding	Low transport capabilities; obstructed access to the part
Electrostatic	Restricted to low temperature applications; no dust particles; low humidity rate	Clean environment required	–
Optical	Transparent surrounding medium; better control in liquid	–	Very restrictive limitations on the particles and environment
Bernoulli	Not in vacuum; no dust particles	Need for an external pressurized air supply; special filter and recirculation system	Poor lateral stability
Air cushion	Not in vacuum; no dust particles	Need for an external pressurized air supply; special filter and recirculation system	No lateral stability
Standing wave	Not in vacuum; non-intrusive technique	Very compact system; ergonomy reduced by the presence of a reflector	Gripping, orienting positioning and releasing parts with the radial centring force and by rotating or translating the reflector
Near-field	Not in vacuum; non-intrusive technique	Very compact system	Guiding and transporting parts with travelling waves

- stability of the equilibrium positions,
- harmful interactions with the surrounding area,
- working environment limitations,
- complexity and compactness of mechanical design,
- microhandling capabilities.

According to [24], the various principles should be assessed considering other criteria such as surface properties, cycle time, positioning accuracy, etc. Unfortunately, in most cases no information has been supplied by authors.

Tables 1 and 2 summarize most of the information collected concerning the different levitation principles. We indicate *not limited* for the levitation force when the principle is able to deliver forces that are quite larger than the weight of microcomponents considered. The symbol – is used when no reliable information is found on the topic.

The preliminary results of the literature review lead to the choice of acoustic levitation which seems to be the most appropriate for microassembly purposes.

In what follows, electric and magnetic levitations have been put aside because they do not easily apply to all kinds of materials. Moreover, they always require a control loop to ensure stability. Optical levitation is restricted to very small and relatively transparent particles in a transparent surrounding liquid medium. The restrictions on the particles and environment are clearly too important for the purpose of microassembly. This principle also hardly generates 1 nN forces, which are too small to manipulate components with a size greater than 100 μm. A choice has still to be made between aerodynamic levitation and ultrasonic acoustical levitation. Aerodynamic levitation presents poor lateral stability and requires a more complex implementation because it needs an external source of pressurized air.

On the other hand, there is a real research interest in the acoustical levitation field. It is not completely understood yet since it involves complex theories of non-linear acoustics. A great deal of confusion is generated by this phenomenon; bright ideas as well as erroneous assumptions and conclusions have been published on the subject. The problem is located at the intersection of fluid dynamics, structure dynamics and piezoelectricity, and is thus multidisciplinary.

In this respect, we have decided to focus on ultrasonic acoustical levitation. The choice between the two acoustic configurations has not been made yet. While standing wave levitation is most suitable for gripping, orienting, positioning and releasing small parts of various shapes, near-field levitation is more appropriate for guiding and transporting planar parts. The choice of the principle will then basically fix the microassembly application to be developed.

5. Applications

This section presents the various applications of levitation based on the previously described principles. The first subsection includes applications and case studies found in scientific literature. The second one proposes some patented applications as far as ultrasonic acoustical levitation is concerned.

Applications presented here have been restricted to *micro*applications, dealing with small parts and forces. Obviously, the complete application field is not limited to this. A very famous example of macroscopic levitation for transportation is the magnetic train levitation. Germany has developed the *transrapid*, which is an example of electromagnetic system. The Japanese magnetic levitation development is similar but uses electrodynamic levitation [57].

5.1. Literature applications

Despite the wide range of principles and applications, several fields emerge and can be fitted into three main domains: containerless processing, contactless guiding and handling systems.

5.1.1. Containerless processing of materials

This category includes applications where special experimental conditions need to be reached in order to perform property measurements or special operations, mainly in the field of material science. All physical principles are suitable except aerodynamic levitation which inherently contaminates the sample.

Motokawa [31] suspends water in high magnetic fields and studies the crystallization process. Bar-Ziv [37] describes an electrodynamic levitation system designed for studying high temperature kinetics and called the electrodynamic chamber. Liquid or solid particles up to 200 μm are suspended. Bancel [40] proposes the use of optical gripping to trap and displace single seed (up to 50 μm in size) for crystal growth application. Gao [29] uses standing wave acoustic levitation to perform containerless melting and solidification of a liquid crystal. Spheres of 3 mm in diameter are successfully levitated. Daidžić [36] studies non-linear water droplet oscillations and evaporation in an ultrasonic levitator. Finally, let us mention the case of a miniaturized acoustical positioning system [58], commercialized by Dantec Dynamics, which can be used in analytical chemistry to study crystallization processes for example, with spherical samples of sizes ranging between 15 μm and 2.5 mm [59].

5.1.2. Contactless guiding and levitated rotors

This kind of application uses the frictionless motion arising from levitation to set up new guiding systems with linear or rotating movement. All physical principles are suitable except optical levitation which is restricted to the handling of small spheres.

Kang [25] develops a magnetic suspension positioning stage driven by a linear permanent magnet synchronous motor. The stage can move 60 mm forward or backward with an accuracy of up to 10 nm. Jeon [60] implements an electrostatically suspended induction motor. The stator electrodes exert the electrostatic forces to the rotor and are divided into a part responsible for suspension and one for rotation. The rotor is suspended 0.3 mm below the stator and is rotated at an approximative speed of 70 rpm. Wiesendanger [50] proposes squeeze film air bearings using piezoelectric bending elements. A linear bearing is first developed to perform acoustical contactless guiding with a total load capacity of 30 N. A rotational bearing is derived to levitate the rotor of a brushless DC motor up to 15,000 rpm. Hu [61] proposes a non-contact ultrasonic motor with an ultrasonically levitated rotor where both driving force and levitation force are generated by an acoustic travelling wave. The revolution speed exceeds 3200 rpm for an air gap between the rotor and the stator lower than 0.1 mm.

5.1.3. Handling and transfer systems

A special interest is taken in this application domain since it concerns a large industrial field. All physical principles without exception can be used.

Park [28] develops a contactless magnetically levitated silicon wafer transport system designed for 203 mm wafers with a mass of around 50 g. Fantoni [2] presents some results on electrostatic alignment of cylinders with diameters up to 1 mm and lengths up to 4 mm. This system could be applied to feeding and is a contactless alignment system rather than a contactless levitation system. Rambin [62] experiments an optical microassembly layout. Repetitive assembly functions can be performed with several laser beams. A microgear with an outer diameter of 300 μm and a shaft of 60 μm in diameter are manipulated and assembled in silicone oil. Erzincanli [27] describes a contactless robotic handling system for non-rigid materials such as food products using the Bernoulli effect. Gengenbach [46] presents an example of feeder for contactless transport of microparts based on air cushion levitation. Horizontal motion is provided with an adapted electric field. Höppner [47] proposes a standing wave manipulation for the handling of a small gear. The size of the component is 3 mm in diameter for the wheel and 0.8 mm for the spindle. Reinhart [48] gives an application of the squeeze film effect for the transport of 200 mm wafers without contact where the lift and feed functionalities can be fully decoupled by using single vibrators. Hashimoto [54] proposes a contactless transporting system using flexural travelling waves. The vibration generates forces for levitating and accelerating the handled component. A square bakelite plate of 70 mm, 2 mm thick and 7.6 g in weight, is successfully transported. Zaeh [26] describes a hybrid contact free gripper based on the balance of vacuum suction and squeeze film repulsion for the handling of 5 mm^3 structured dices.

5.2. Patented applications

Several applications have already been patented. Since we intend to limit ourselves to the development of models for the acoustical levitation, the patents presented here are restricted to this kind of levitation. Here again, we classify patents in three main groups: experiments to support theory, solutions to control the position and handling systems.

5.2.1. Experiments to support theory

This category includes demonstration experiments, applications to corroborate a theory and to make measurements of predicted values or applications to provide indirect measurements.

With regard to the ultrasonic standing wave levitation, Barmatz [63] shows an experimental way to determine the equilibrium position and orientation of a non-spherical component by determining the minimal centre resonant frequency. Watkins [64] proposes a solution to track linear and rotation motions by measuring the modulation of the acoustic energy. The restoring force constant of the field can be determined, as well as the surface tension and viscosity of a handled drop. Mitome [65] claims an experimental visualization method for a three-dimensional standing wave acoustic field that could be used to validate simulation results.

5.2.2. Solutions to control the position

This category gathers technical solutions to control the position and the orientation of the levitated sample. Many patents are related to microgravity applications developed through NASA projects.

Barmatz [66] proposes the use of a resonant chamber with angled side walls to control lateral positioning of the levitated component. The author claims a method to damp or increase the oscillations of a levitated component [67]. He also presents a technical solution to control the orientation and rotation of a levitated component by making the acoustic field non-symmetrical [68]. Kaduchak [69] proposes a resonator chamber with variable geometry to levitate and concentrate components. Takasan [70] claims a method for controlling the movements of a levitated component in the near-field.

5.2.3. Handling, positioning, orientation and transfer systems

Höppner [71] presents a solution for the transfer of planar substrates between two stations. Hashimoto [72–74] describes an object transporting apparatus with an object levitating system together with their processes. Takasan [75] claims a non-contact unloading system to transfer a component between two non-contact conveying systems.

5.3. Conclusions on acoustical applications

As far as acoustic levitation is concerned, it can be concluded that the two configurations for acoustic levitation are not suited for every application field: the standing wave levitation is appropriate for containerless processing of materials and handling systems, whereas squeeze film levitation is rather suitable to guiding or transfer systems. These differences originate in the principles themselves. Standing wave levitation can easily be used to perform movements in translation and rotation in a three-dimensional space while squeeze film is naturally confined to a two-dimensional movement.

6. Models for ultrasonic acoustical levitation

As previously explained and justified, we have decided to focus on ultrasonic acoustical levitation. This section presents its numerous models with their assumptions and limitations.

A body placed in a sound field will experience a force owing to the relative motion of the body and the fluid elements in the medium. This force arises from the scattering of the sound waves by the body and is equal to the rate of momentum change through any surface enclosing the body [76].

Acoustic radiation pressure is a topic of non-linear acoustics which was discovered a whole century after the light radiation pressure in optics. This is mainly due to the non-linear nature of the acoustic radiation pressure. In fact, this effect is inherently suppressed by the linearization while resolving the wave-equation. A second order approximation is needed to obtain a small but finite diagonal tensor which represents the static acoustic pressure. The problem can be solved to higher order, but calculations are generally restricted to second order approximations.

Both kinds of acoustical levitation (standing wave and squeeze film) can be explained by the following non-linear features in a sound field: Rayleigh radiation pressure and Langevin radiation pressure. These non-linear terms come from the non-linearity of the thermodynamic state equation for a barotropic fluid

$$p = f(\rho) \tag{1}$$

and the convection term of the Euler equation [26] for a non-viscous Newtonian fluid

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\vec{v} = -\frac{\vec{\nabla} p}{\rho} \tag{2}$$

where $\vec{v}$ is the velocity, p the pressure and ρ the density. Both terms are neglected in linear acoustics due to their small values. However, they are responsible for a second order average pressure in the sound field. From these fundamentals, various explanation models and approximations have been derived.

With this object, two fundamental approaches to an estimation of the acoustic radiation pressure and the levitation force are possible:

- solving the linear wave equation exact to first order

$$\nabla^2 \phi = \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} \tag{3}$$

where ϕ is the velocity potential $\vec{v} = -\vec{\nabla}\phi$ and c the sound velocity. Results can then be used to evaluate acoustic radiation pressure exact to the second order.

- directly solving the non-linear wave equation exact to the second order [77]

$$\nabla^2\phi = \frac{1}{c^2}\frac{D^2\phi}{Dt^2} + \frac{1}{2c^2}\left[\left(\frac{\partial\phi}{\partial x}\right)^2 + \left(\frac{\partial\phi}{\partial y}\right)^2 + \left(\frac{\partial\phi}{\partial z}\right)^2\right] \quad (4)$$

where $\frac{D}{Dt}$ is the total time derivative.

Most authors follow the first approach, as for example King [77], whereas some of them prefer the second one, as for example Westervelt [78].

In the first approach, the problem is divided into two successive points. An expression for the acoustic radiation pressure valid to the second order has first to be established starting from the general equations of fluid dynamics. This development has to be done only once, and King [77] derives the pressure variation δp in the medium

$$\delta p = \rho_0 \partial_t \phi + \frac{1}{2}\frac{\rho_0}{c^2}(\partial_t\phi)^2 - \frac{1}{2}\rho_0 v^2 \quad (5)$$

where ρ_0 is the density of the surrounding medium and $v = \|\vec{v}\| = \sqrt{v_x^2 + v_y^2 + v_z^2}$ is the velocity amplitude. This pressure increment δp has to be integrated over the object surface to get the levitation force. With a second order approximation of the pressure as a function of the velocity potential, it is sufficiently accurate to calculate the velocity potential ϕ from the approximate linear wave Eq. (3).

To this end, the velocity potential ϕ is evaluated by solving the scattering problem. The latter is simplified by using the linear Helmholtz wave equation. However, the solution of this equation depends on the boundary conditions of the problem. The simplest one is given in terms of a plane wave, but every kind of incident wave has to be considered (plane progressive wave, plane standing wave, spherical wave, arbitrary field ...). When such a wave *hits* an obstacle, a scattering of acoustic waves in all directions occurs. Linear superposition of the incident and scattered wave will give the distribution of the total pressure or the velocity potential.

Of course, the solution of the scattering problem will sharply depend on the geometry of the scattering object. Moreover, the mathematics involved in solving scattering problems of arbitrary geometry are difficult even in the case of linear wave equation. Typical scattering objects considered in the calculations are small spheres or plates. For standing wave levitators, the standard part to be handled is a small sphere whereas near-field levitation requires a part with a planar surface. This is the first reason why models are presented separately for the two kinds of ultrasonic acoustical levitation.

We first very briefly describe the previous works of several authors as far as standing wave levitation is concerned. Near-field levitation has been discovered and exploited more recently. The results found in literature to model this last phenomenon are described in the second subsection.

6.1. Standing wave levitation

King [77] is the first to present a systematic theoretical development enabling the calculation of acoustic radiation pressure. He uses the first approach described above and derives an expression of the radiation pressure exact to the second order terms. In these circumstances, it is sufficiently accurate to calculate the velocity potential ϕ from the approximate linear Helmholtz wave equation. The model is highly simplified and only valid for small rigid spheres in a plane wave. The spheres are supposed to be small compared to the wavelength, and the effects of the sphere compressibility and the medium viscosity are not taken into account. However, analytical calculations are already very complex. King shows that the forces exerted by standing waves are much stronger than those generated by travelling waves of the same amplitude.

For a plane progressive wave, the obtained mean force is

$$\overline{P_K^1} = 4(\pi a^2)(ka)^4 F_K^1\left(\frac{\rho_0}{\rho_1}\right)\overline{E} \quad (6)$$

where a is the sphere radius, $k = \frac{\omega}{c}$ the wave number, F_K^1 is the so-called [77] *relative density factor* for a plane progressive wave and $\overline{E}$ the mean total energy density in the wave

$$\overline{E} = \frac{1}{2}\rho_0 k^2 |A|^2 \quad \text{and} \quad F_K^1\left(\frac{\rho_0}{\rho_1}\right) = \frac{1+\frac{2}{9}(1-\frac{\rho_0}{\rho_1})^2}{(2+\frac{\rho_0}{\rho_1})^2} \quad (7)$$

where $|A|$ is the incident velocity potential amplitude; ρ_0 and ρ_1 are respectively the densities of the surrounding medium and the sphere.

For a plane stationary wave, the obtained mean force is

$$\overline{P_K^2} = 2(\pi a^2)(ka)\,\sin(2kh)F_K^2\left(\frac{\rho_0}{\rho_1}\right)\overline{E} \quad (8)$$

where F_K^2 is the relative density factor for a plane stationary wave

$$F_K^2\left(\frac{\rho_0}{\rho_1}\right) = \frac{1+\frac{2}{3}(1-\frac{\rho_0}{\rho_1})}{2+\frac{\rho_0}{\rho_1}} \quad (9)$$

Westervelt [76] derives a general expression for acoustic radiation forces valid for parts of any shape, where the force is evaluated in terms of a surface integral. The author also shows that the boundary layer losses can generate forces being several orders of magnitude larger than classical acoustic forces. He uses the second approach which consists in solving the second order wave equation directly [78,79].

Improvements have been added later. The sphere size, the sphere compressibility or elasticity, the properties of the sound field and the fluid can be taken into account. Embleton [80,81] presents King's previous work in a form which is applicable to a progressive spherical and cylindrical sound field. The radiation force calculated is valid for all ratios of sound wavelength to obstacle radius. Furthermore, Yosioka

[82] extends the method developed by King to include the sphere compressibility. In the first place, the author gives some results in the case of a small solid sphere and shows that dense spheres tend to accumulate at the pressure node while light ones accumulate at the pressure anti-node. Yosioka [83] next studies radiation pressure on bubbles and shows that bubbles larger than the resonance radius accumulate at the pressure nodes and smaller ones at the loops. The models reviewed in this study mainly concern dense particles. The problem of bubbles comes out of the scope of this work. Gor'kov [84] presents a very simple method to evaluate the radiation force exerted by an arbitrary acoustic field on a compressible sphere by means of a force potential. The method deviates from those presented by King and Yosioka and starts from the fact that the force is equal to the average flux of momentum through any closed surface in the fluid which encloses the particle. Barmatz [85] applies the theory developed by Gor'kov and derives force expressions for arbitrary standing wave modes in rectangular, cylindrical and spherical geometries. Nyborg [86] recalculates the radiation force from the general methods and expresses results in terms of the time-averaged densities of kinematic and potential energies. Hasewaga [87] introduces the material elasticity and the sound absorption in the sphere. The size of the sphere is not necessarily small compared to the wavelength. Alekseev [88] derives a simple expression for an incident sound field having an arbitrary form in the vicinity of the spheres. The mutual interaction of particles is then investigated. Doinikov [89] evaluates the same force for a spherical sound field in a viscous fluid. The method is then generalized to an axisymmetrical sound field in a viscous and heat-conducting fluid [90].

Brillouin [91] demonstrates that the so-called radiation pressure is in fact a diagonal tensor with diagonal terms being all different. He introduces the notion of radiation tensor and shows that the phenomenon is not correlated with the density of momentum carried by the wave but with the flux of momentum. Beyer [92] confirms that the radiation pressure is a tensor. He points out several errors made on the subject in the past and explains the differences between the Rayleigh and the Langevin radiation pressures.

Magill [93] works out approximate scaling laws for optimum sound field characteristics as a function of sample density and radius. Magill also points out the fact that acoustic radiation forces increase linearly with the pressure and that strong forces can be applied when working in a compressed environment.

Czyż [94] studies the motion of particles under the influence of the drift forces occurring in a standing wave field. He considers the drift forces arising from the oscillation asymmetry, the acoustic radiation pressure, the temperature dependence of the viscosity and the distortion of the wave form due to the second harmonic. The various force amplitudes are compared with gravity. The acoustic radiation forces are shown to be the most significant ones for particles with a radius exceeding some 50 μm.

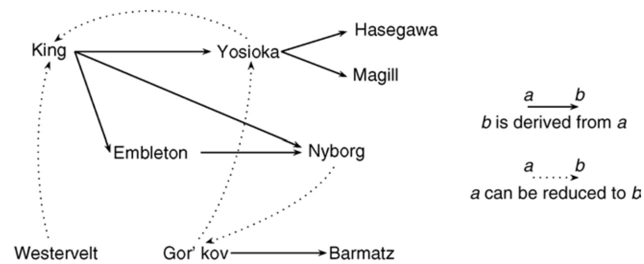

Fig. 7. Overview of the main models for acoustic standing wave levitation.

The most important models for acoustical standing wave levitation are related to each others in Fig. 7. Two kinds of relation are explicitly indicated on this graph by arrows of different stroke. This graphically expresses some considerations discussed here above in detail.

6.2. Near-field levitation

When working in the region near the piston sound source, called Fresnel region, the complex acoustic diffraction disturbs the wave field. This can result in misunderstood displacements of the lowest particles in a standing wave levitator [93]. The previously described calculations need to be revised in this area.

Hasegawa [95] calculates the acoustic radiation pressure on a small rigid sphere situated on the axis of a circular piston vibrator including the points in the near zone where the diffraction effects can no longer be neglected. The velocity potential of incident waves in the near-field is determined, thereby allowing the use of conventional scattering theory to calculate the radiation force. The present theory is also applicable to elastic or compressible spheres. However, it is not so in the cases where the possible effects of the scattered waves on the vibrating piston cannot be negligible.

Moreover, in squeeze film, the parts are held without reflector and are supposed to have a planar bottom surface. The boundary conditions of the problem are then totally different.

Chu [96] summarizes the confusion generated by acoustic radiation pressure. He calculates the Rayleigh radiation pressure successively on a plane target perfectly absorbing, partially reflecting and perfectly reflecting; he also compares Rayleigh and Langevin radiation pressures. The confusion source comes from the failure to distinguish the Eulerian and the Lagrangian means.

Wiesendanger [50] first explains the basic working principle of squeeze film with very simple models. He considers infinite plates and explains how the non-linearity of the polytropic transformation $pV^n = cst$ leads to a levitation pressure between a vibrating and a free plate. This result is illustrated in Fig. 8 where the first quadrant contains the polytropic transformation, the fourth quadrant shows the harmonic distance oscillation between the plates. The non-harmonic pressure oscillation is derived in quadrant two. The mean pressure $\overline{p}$

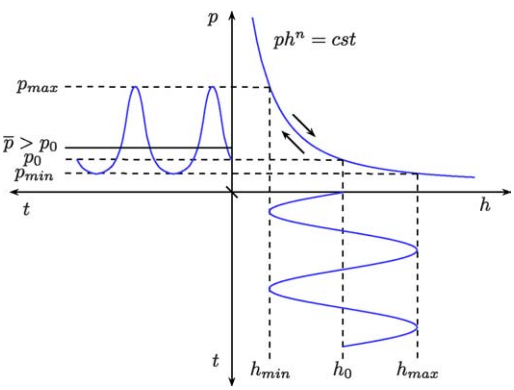

Fig. 8. Non-linearity of the polytropic transformation [50].

is larger than the atmospheric pressure p_0. Next, the author shows how an overpressure can exist by performing a calculation of the volume flow between two infinitely wide plates by the mean of a Poiseuille flow. These two simple models can only qualitatively explain the levitation force. The general Reynolds equation is then derived and resolved analytically in particular cases and numerically to achieve quantitative results on the forces. This equation comes from the classical Navier–Stokes equations with the additional assumptions of the lubrication theory [97].

Minikes [98] solves the coupled dynamic problem of a vibrating piezoelectric disk generating an air squeeze film. The piezoelectric part is modelled by finite elements while the squeeze film phenomenon is represented by means of finite-difference equations to model a variant of the Reynolds equation and the calculations are preformed numerically.

Koike and Hashimoto [51,53] theoretically investigate the near-field acoustic levitation of planar objects. They first consider the case of in-phase vibrations and derive the governing equation from the linear wave equation. An expression of the time average force per unit area exerted on a levitated object is obtained as a function of the levitation distance and approximated for small levitation heights as in near-field levitation. The authors then consider acoustic levitation using flexural mode and perform similar calculations. However, the assumptions made in this context lead to significant differences for the flexural mode.

6.3. Comparison of the various models

Several models describing the acoustic levitation are presented in the preceding subsections. The models have been assessed according to several criteria such as

- the ability to qualitatively or quantitatively predict the levitation force,
- the levitated component shape and size limitations,
- the limitations on component properties,
- the assumptions on the surrounding environment,
- the restrictions on the sound field,
- the ability to handle orientation and centring effects.

This gives some indication of the considerable work which has already been completed and lists a number of guidelines for further developments in modelling acoustic forces in a microassembly task. Several generalizations have still to be made to achieve this goal and a wide overview of the existing techniques is absolutely necessary.

Other criteria can be useful such as the various implementation difficulties, the computing time and the agreement with the real physical phenomenon.

7. Conclusions and future work

7.1. Conclusions

The present work starts with the acknowledgment of the microassembly importance in current industrial developments. One of the main problems it undergoes at a microscale arises from the adhesion due to surface forces. We propose four main strategies in order to tackle these surface force effects: they can be reduced and overcome while releasing object or they can be used to achieve the picking task. The fourth approach consists in completely avoiding the mechanical contact between the effector and the object. Various advantages of non-contact handling are exposed not only for microassembly purpose. This paper finally justifies the interest shown in non-contact within the framework of microassembly.

The various physical principles suitable for contactless handling are then reviewed and described: magnetic, electric, optical, aerodynamic and acoustic levitations. An evaluation of the physical principles have led to the choice of the ultrasonic acoustical levitation for microassembly. Acoustic levitation exists in two main configurations: standing wave levitation and near-field levitation.

Applications of non-contact manipulation are then reviewed and classified into several groups. The study of scientific literature leads to three main categories of applications: containerless processing of materials, contactless guiding and handling systems. On the other hand, as far as acoustic levitation is concerned, the report on the patented applications leads to the following classification: experiments to support theory, solutions to control the position and again handling systems. The review of application fields results in the following conclusion: standing wave levitation is better suited for containerless processing of materials and handling systems whereas squeeze film levitation is best fitted for guiding or transfer systems.

An overview of the various models developed is finally presented. Two main strategies can be followed in order to derive acoustic radiation pressure. The first one consists in solving the scattering problem with the linear wave equation and then using results to fit an expression of the radiation pressure valid up to the second order. The second strategy consists in solving directly the non-linear wave equation. Most authors follow the first strategy. As existing models are totally different in both cases, they are presented separately for standing wave and near-field levitation. Some of the numerous models are described with their assumptions and limitations. Guidelines for the comparison of the models are given together with some important criteria.

7.2. Prospects

The overview of the physical principles is likely completed. Nevertheless, the search for patented applications needs to be refined. The list of the various teams who have worked or are currently working on the topic in the world also has to be completed to achieve a wider outlook on the subject. The review of the various models needs to be continued.

Another interesting work would be the generalization of a single model to be applied to both standing wave and squeeze film levitations. The unified model will then be implemented to perform calculations of the levitation forces and stable positions as a function of the amplitude and frequency of the vibrations, the sound wave features, the shape and density of the object and other parameters.

The final goal is the implementation of a simulation tool devoted to the design of non-contact handling system based on acoustical levitation. This simulation tool will be used to design a prototype of contactless handling system suitable for microcomponents. It should be as general as possible to allow a potential use in industrial design.

Furthermore, the developed model must be enriched to include common effects needed in microassembly. The model should for example take the following topics into account: the centring and orientation effects of the part due to a non-ideal sound wave, the effect of a non-harmonic power supply of the vibration source, the possible effect of roughness and, of course, the effect of a complicated shape of the parts to be handled. All these imperfections and complications are necessary to efficiently model the real manipulation task.

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