ISSN (e): 2250 – 3005 || Volume, 07 || Issue, 11|| November – 2017 ||
International Journal of Computational Engineering Research (IJCER)

Near-field acoustic levitation and applications to bearings: acritical review

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ABSTRACT:
The importance to industry of non-contact bearings is growing rapidly as the demand for high-speedandhigh-precisionmanufacturingequipmentincreases.Asarecentlydevelopednon-contacttechnology, near-field acoustic levitation (NFAL) has drawn much attention for the advantages itoffers,includingnorequirementforanexternalpressurizedairsupply,itscompactstructure,anditsabilitytoadapttoitsenvironment.Inthispaper,theworkingmechanismofNFALisintroducedindetailandcomparedtoallexistingnon-contacttechnologiestodemonstrateitsversatilityandpotential for practical applications in industry. The fundamental theory of NFAL, including gasfilmlubricationtheoryandacousticradiationpressuretheoryispresented.Then,thecurrentstate-of-the-artofthedesignanddevelopmentofsqueezefilmairbearingsbasedonNFALisreviewed.Finally,futuretrendsandobstaclestomorewidespreadusearediscussed.
Keywords:acousticlevitation,non-contacttechnology,bearing,measuringandmanufacturingequipment,squeezefilm

INTRODUCTION

As the trend in equipment moves toward intelligent develop-ment,therequirementforhighlyaccuratesupportingelementsfor precise positioning systems, measuring instruments, andmanufacturingequipmentisincreasing[1–4].Inparticular,the

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accuracyandstiffnessofthetransportationandrotationsystemshouldkeepupwiththedevelopmentofindustrialtechnology.Ascorecomponents,bearingsdirectlyaffecttheperformanceand service life of a system. Many non-contact technologieshave been extensively developed to improve the rotation acc-uracyandstabilityofsystems.
Currentlyavailablenon-contactbearingsincludeaero-static and aerodynamic bearings, as well as magnetic bear-ings.However,thesetraditionalbearingshavemanydrawbacks. Aerostatic bearings require a clean air supplysystemduringoperation,whichnotonlyoccupiesmorespacebut also increases the cost [5]. Aerodynamic bearings sufferseverefrictionandwearonthesurfaceduringthestart-upand

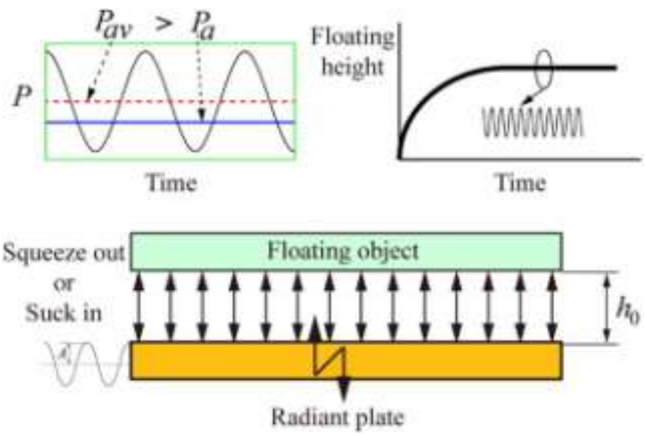

Figure 1.Schematicdiagramofsqueezefilmlevitation.

stopstages[6–9].Magneticbearingsnotonlyneedacomplexstructure to produce a strong magnetic field but also have anuncertaininfluenceontheinstrument/equipmentduetothe magneticflux[10].

The squeeze film effect can be observed in many engi-neering instruments, e.g. in dampers, gudgeon pin bearings,gears, and lubricated parts of living bodies, etc. This workingprinciplecanbeusedtolevitateobjects,asshowninfigure1.Ifweputanobjectonaplaneanddrivetheplanetovibrate inthedirectionnormaltoitssurfacewithavibrationgenerator,theairwithin the gap between the plane and the object will be peri-odicallysuckedinandsqueezedout.Thetime-averagedpressureforoneperiodinthegapwillbehigherthanambientpressureandthusgeneratinglevitationforcetosupportloadandlifttheobject.Thisphenomenoniscallednear-fieldacousticlevitation (NFAL) (also called squeeze film levitation), which may over-comethedrawbacksoftraditionalnon-contacttechnologies.

In 1886, Reynolds [11] first explained that the squeezeeffect was an important mechanism for the generation ofpressure in lubricating film. However, since then, researchershavenotappreciatedthesqueezeeffectbecausetherehasbeennosuitablevibrationgenerator.Withthedevelopmentofpiezoelectric actuators, which can be used as high-efficiencyvibrationgenerators,thepotentialofsqueezefilmtechnologyas a non-contact levitation method was rediscovered. In the1960s, Tipei [12] investigated the gas squeeze film theory.Then,sometheoreticalandexperimentalworkswerereported by other authors [13–17], which validated the feasibility ofsqueezefilmlevitation.Sincethen,acousticlevitationhasbeeninvestigated by researchers [18–20]. In recent years, manykindsofacousticlevitationequipmentshavebeendesigned, manufactured, and widely applied in various fields, such asmicroassembly[21],biomaterials[22],analyticalchemistry [23,24],materialsciences[25],andpharmaceuticals[26].

Some papers on squeeze film air bearings (SFABs) havebeen recently reported, which can provide us with a morecomprehensiveunderstandingofSFABsfrombothscientific and practical perspectives. The purpose of this review is notonly to summarize theoretical modeling, the basic principle,structuredesign,andapplicationsofNFAL,but,moreimportantly,topromotetheapplicationinengineering.

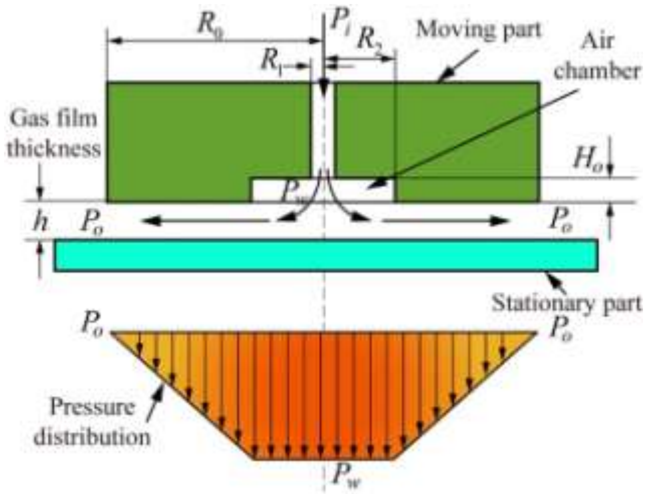

Figure2.Schematicdiagramofoperatingprincipleofaerostaticbearing.

Thisreviewisorganizedintosevensections.Insection2,four types of non-contact bearing technologies are describedanddiscussed,includingaerostaticbearings,aerodynamicbearings, magnetic bearings, and SFABs. Section 3 reviewsthehistoryofthedevelopmentofSFABsandsummarizesthestateoftheartinNFALtheory.Section4summarizes severalcommon types of SFABs. The operating principle of hybridSFABsisintroducedinsection5,pointingoutthattheworking mode of this kind of hybrid bearing can be chosenfreely according to the need. Discussion and future trends ofSFABs are presented in section 6. Finally, conclusions areprovidedinsection7.

1. Workingmechanismofseveralnon-contactbearingtechnologies

Non-contact bearing technologies are widely used in high-precision measuring and manufacturing equipment due to theabsence of contact and friction forces between stationary andmovingcomponents.Fourtypesofnon-contactbearingtechnologies are briefly described, focusing on their workingcharacteristicsandbasicfeatures.

Aerostaticbearings

Aerostaticbearingshavebeensuccessfullyusedinhighprecision applications, e.g. precise moving devices, machinetools, manufacturing equipment, and measuring instruments,etc. Figure 2 shows a schematic diagram of a typical circularaerostaticbearingwithacentralorificerestrictorandacylindrical recess. The radius of the bearing is R_0, R_1 is theradius of the supply orifice, and R_2 and H_0 refer to the size ofthe air chamber. The initial gas film thickness is h. Pressur-izedairissuppliedthroughacentralorifice-specificrestrictorinto the clearance between the stationary part and the surfaceofthebearing.TheinitialpressureoftheinletoftherestrictorisP$_i$.Afterenteringthechamber,theairpressuredropstoP$_w$.Finally,theairisdischargedtothesurroundingambientair

hrough the exit edges of the bearing gap; and the pressuregradually decreases to P_o. Aerostatic bearings are also calledexternally pressurized air bearings as the two surfaces areseparated by an air film generated by an external air supplysystem.

The restrictor and pressure distribution in the clearancehave an obvious influence on the load-carrying capacity andstiffnessofaerostaticbearings.Therefore,studiesontherestrictors and pressure distribution have been reported bymany researchers. An aerostatic flat pad bearing with annularorifice restrictors was investigated by Stout [27] who showedthatanaerostaticbearingwithannularorificerestrictorswasabetter choice if the designer was concerned about pneumatichammer instability. Stout et al [28] proposed a spherical gasbearing with slot restrictors. The optimum design conditionsweredeterminedbyanalyzingthebearinggeometryandpressure ratio. The results showed that the bearing has amaximumradialloadcapacitywhenthedesignpressureratiois in the region of 0.5. However, instability will occur whenthedirectionoftheeccentricityistowardanyoneslot.

Nakamura et al [29] presented experiments and predic-tions for an aerostatic rectangular thrust bearing with com-poundrestrictorswhichcombinesafeed-holerestrictorwithagroove compensation restrictor. In 1964, Mori et al [30] useda test rig to study the behavior of circular thrust gas bearingswith a porous bearing surface. The pressure distribution andtheload-carryingcapacityweremeasured.Theoreticalresultsshowed good agreement with the experimental results. Since1963, researchers such as Mori et al [31], Kassabet al [32],Yoshimoto et al [33] and Belforteet al [34] have studied thepressuredistributioninthebearingclearanceinordertoimprove the stiffness and load-carrying capacity of aerostaticbearings.

Aerostaticbearingscaneffectivelyovercomefrictionandwearissuesduringtheworkingprocess.However,pneumatichammer vibration [35] and vortex shedding [36] may occurduring the working process. Furthermore, aerostatic bearingsrequire a clean air supply system during operation, which notonlyoccupyingmorespacebutalsoincreasingthecost.

Aerodynamicbearings

Aerodynamic bearings work on the principle of aerodynamiceffect, which is the best known pressure generation mech-anismintheflowofafluid.Theoperatingprincipleofaerodynamicbearingsisillustratedinfigure3.Atiltinguppersurface, W_1W_2, is stationary; and a lower surface, Z_1Z_2, ismoving relative to the upper surface in the x direction with avelocity of u_1. The clearance is filled with gas lubricant. Theentrance clearance and exit clearance between the two sur-faces are h_0 and h_2, respectively. The gas film thickness at acertain point in the middle is h_1. When the lower surfacemoves at the velocity, u_1, the clearance along the direction ofmotiondecreasesgradually;andthefluidflowsfromthelargeclearance to the small clearance forming convergent clear-ance. The inflow fluid is more than the outflow fluid becauseh$_0$ is larger than h_2, and the flow is clearly discontinuous.Therefore,thepressureisgeneratedbytheviscousshearingof

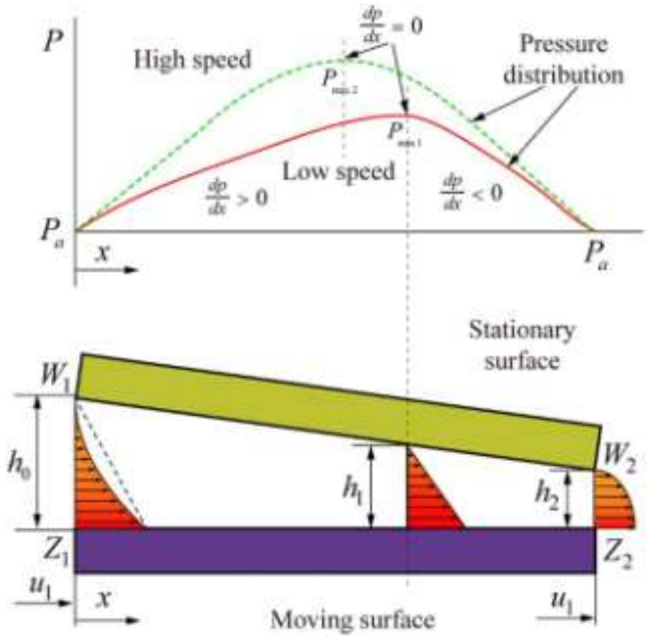

Figure3.Schematicdiagramoftheoperatingprincipleofaerodynamicbearing.

gasfilmintheclearance,whichisthesourceofload-carryingcapacity. Note that if the stationary surface is parallel to themoving surface, there is no pressure generation between thetwosurfaces.Inotherwords,theaerodynamiceffectcanonlybe generated when there is a tilting angle between the twosurfaces.Highrelativespeedcanobviouslyenhancetheaerodynamiceffect.

Early research on air lubrication technology was con-ducted by Willis [37], who experimentally investigated theairflow status between two parallel plane surfaces. Then, thefamousReynoldsequations,combiningthesimplifiedNavier-Stokes equations with a continuity equation, were proposedby Reynolds in 1886 [11]. In 1897, Kingsbury [38] verifiedthefeasibilityofagasbearingthroughexperimentalresearch.The reference [39] combined the Reynolds equation and thecompressible gas equations to present the basic calculationmodel for gas lubrication. After that, Katto and Soda [40]gave an analytical expression for the load-carrying capacityundertheassumptionofisothermalandinfinitelylongbearingconditions.

The load-carrying capacity and half-speed whirl are twoimportantissuesforaerodynamicbearings.Theload-carryingcapacity of an aerodynamic bearing is usually much less thanthatofoil-lubricatedbearingsduetotheextremelylowviscosity of air [41]. Half-speed whirl, which is caused by aself-excitedfilmwhirl,oftenoccursforhigh-speedaero-dynamicbearings[42,43].Thisphenomenonisusuallyfoundto be the main reason for the instability of the rotor bearingsystem.

In order to improve bearing performance, researchersconducted their investigations into the air pressure distribu-
tionandsupportingstructures,respectively.Aportionofresearcherschangedtheairpressuredistributioninthegapby introducinggroovesintothebearingorrotorsurface[44–48].

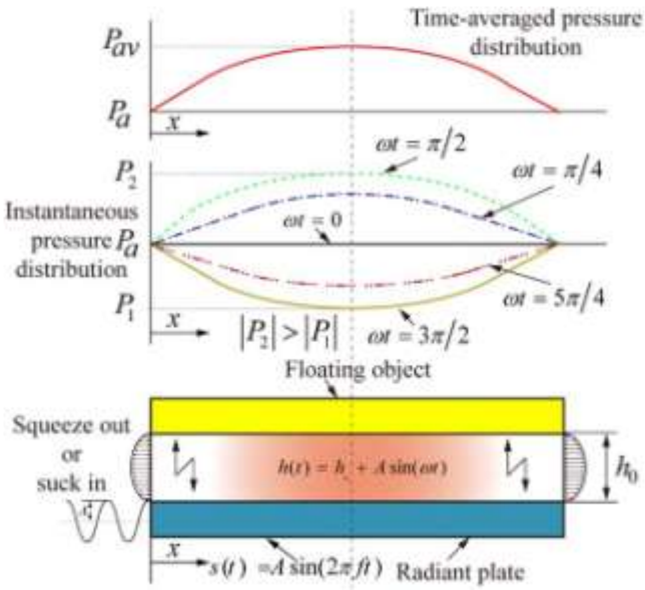

Figure 4.Schematic diagram of the operating principle of magneticbearing,(a)schematicdiagramofmagneticlevitationand(b)activemagneticbearing.

Groovedbearingscanenhancetheload-carryingcapacityandfilm damping effect. Other researchers changed the support-ing structures by introducing a tilting pad or compliant metalmaterial.Tiltingpadgasbearingshavebeensuccessfullyusedinhigh-speedrotatingmachineryduetotheirinherentstabi-lity [49–52]. Foil gas bearings, which have a flexible bearingsurface constructed with a metal plate, are widely used inmuch turbomachinery [53–57]. However, wear between thetopfoilandshaftsurfaceisinevitablefortypicalfoilbearings; andthusroutinemaintenanceneedstobeconducted.

The gas film force of aerodynamic bearings is normallyinsufficienttosupporttherotorweightduringthestart-upandstopstages.Severefrictionandwearwilloccuronthesurfaceof aerodynamic bearings. The lifetime of aerodynamic bear-ingsisdirectlydependentonthenumberofstartsandstops.

Magneticbearings

Magneticlevitationtechnologyisaphysicalseparationmethod which supports the object without any mechanicalcontact[58,59].Asimpleschematicofmagneticlevitationisshown in figure 4(a). Magnetic bearings can be divided intothreetypesaccordingtotheirworkingprinciples:passive, active, and hybrid. Passive magnetic bearings do not need acontrolsystembutusetheirownpermanentmagneticforceorsuperconductingmagneticforcetosuspendtheshaft,asshowninfigure4(a).Therefore,thestabilityregionofpassivebearing systems is very small since they have no dampingcharacteristics[60–62].Activemagneticbearings(AMBs)

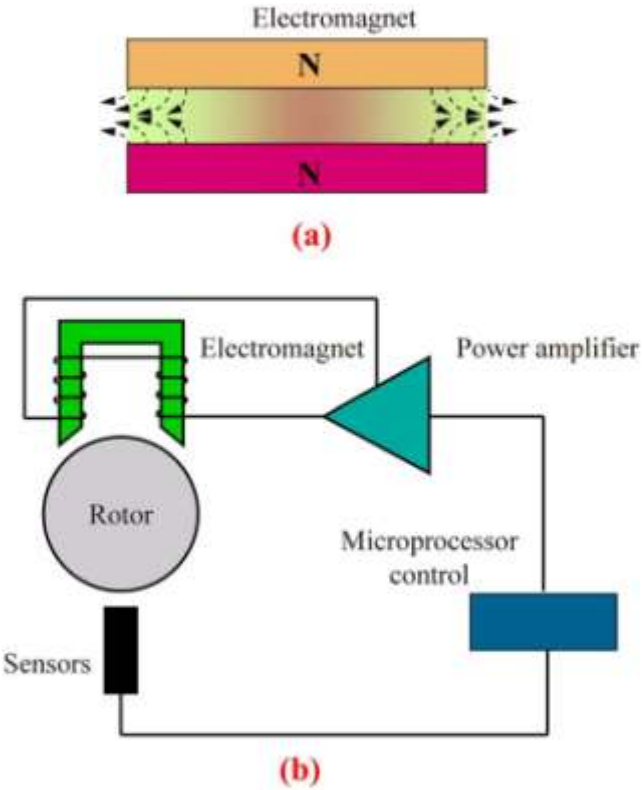

Figure 5.Schematic diagram of operating principle of squeeze filmairbearing.

levitatetherotorbymeansofelectromagneticforce.Theyaremainly composed of rotors, an electromagnet, sensors, con-trollers, and power amplifiers [63–66]. Figure 4(b) shows aschematicdiagramoftheworkingprincipleofanactive electromagnetic bearing. The shaft deviation signal of therotor is detected by the displacement sensor and sent to thecontroller.Thecurrentintheelectromagnetiscontrolledbyapower amplifier, so that the change in the electromagneticforce can make the rotor suspend in the specified position.Compared with passive magnetic bearing, the design of anAMBsystemismorecomplex;butitsdampingcharacteristicsand stability are better. Hybrid magnetic bearing is a kind ofcombinedmagneticbearingsystemthatisformedonthebasisoftheAMB,passivemagneticbearing,andotherauxiliary supportandstablestructures[67–69].Itusesthemagnetic fieldgeneratedbyapermanentmagnettoreplacethestatic biasmagneticfieldofanelectromagnet.Notonlyisthepowerconsumptionofthepoweramplifiersignificantlyreduced,bu tthe number of ampere turns of the electromagnet is reducedby half, the volume of the magnetic bearing is reduced, andthebearingcapacityisimproved.

Squeezefilmairbearings

A schematicdiagram of a system based on squeeze filmlevitation is shown in figure 5. The surface of the radiantplate, which is connected to the vibration generator, is drivento vibrate in the direction normal to the upper plate with highfrequency periodic motion so that the air within the gap isperiodically sucked in and squeezed out. To obtain optimallevitationperformanceofsqueezefilmlevitation,thedistancebetween the radiant plate and floating plate is required to besmall enough to generate high gas pressure. Generally, theclearanceoftensofmicronsisadopted,whichismuchsmaller than the sound wavelength in air. The pressure in thegapvariesperiodically,andthusthepressurevalueis

Table1.Advantagesanddisadvantagesofnon-contactbearings.

Non-contactbearings	Advantages	Disadvantages
Aerostaticbearings	Lowfrictionloss,lowheatgeneration,highmotion accuracy,andlongruntime	Requires a large volume, continuous supply of clean air,and requires external auxiliary devices, and pneumatichammervibration
Aerodynamicbearings	Widespeedrange,highrotationalprecision,andlargetemperatureapplicationrange	High frictionand wearduringthestartand stopstagesofoperation,relativelylowstiffnessanddamping,andrequireshighmachiningaccuracyandhighassemblyerror
Magneticbearings	Lessfrictionalwear,lowvibration,highrotational speed,usefulnessinspecialenvironments,quiet-ness,andlowmaintenance	Producesmagneticflux,cannotbeusedformagneticallysensitiveconfigurations,andneedsastabilitycontrolsystem
Squeeze film airbearings	Lessfrictionalwear,levitationforceatzerospeed,highstability,andcontrollability	Bulkdevice,highenergyconsumption,andshortruntime

different at different times. The instantaneous pressure dis-tributionandtime-averagedpressuredistributionbetweenthetwo flat plates is shown in figure 5. The ambient pressure isset to P_a. The gas film pressure may be either negative orpositive in one cycle, and the sign of the pressure valuedepends on the direction of the squeeze. In addition, the peakvalueofpositivepressureislargerthanthepeakvalueof negativepressure($P_2|>|P_1$).Therefore,time-averagedpressureinoneperiodisgreaterthantheambientpressure, which is the reason for levitation force. Load-carrying capa-cityobtainedfromsqueezefilmlevitationincreasesnon-linearlywiththedecreaseinthefilmthickness.

The analysis of squeeze film levitation theory based ongasfilmlubricationtheorystartedwiththeworkofTipei[12]who obtained the governing equation of squeeze film withthree-dimensional velocity components on the bearing surfacefor a compressible and unsteady lubricating film. Since then,Langlois[13]deducedtheequationgoverningthepressureforideal gas under isothermal conditions and solved the time-dependent Reynolds equation by the perturbation method forafilminwhichfluidinertiaisnegligible.BeckandStrodtman [70] investigated the load-carrying capability of the finitejournal bearing and solved the governing equation by twomethods,i.e.asmall-parameteranalysisandanumericalfinite-difference technique, which are approximate analyticalsolutions. Pan [16] and DiPrima [71] used asymptotic meth-ods to study the characteristics of squeeze film bearings andalso gave approximate solutions. However, the asymptoticmethods have a very limited range for the analysis para-meters, especially in extreme cases. Later, many researchersproposeddifferenttypesofSFABs,whicharepresentedinthefollowingsection.

Comparisonofnon-contactbearings

Eachtypeofnon-contactbearingshasitsowncharacteristics.Acomparison(seetable1) amongthefournon-contactbearingswasconductedtocomparetheirabilitiesinruntime,stability,frictionandwear,motionaccuracy,andenergyconsumption,etc.Ascanbeseen,aerostaticbearingsand aerodynamicbearings provide high motion/rotational accuracyandlowheatgenerationbecausetheyusenon-contact gas support. However, aerostatic bearings require alarge volume, continuous supply of clean air and externalauxiliary devices. Aerodynamic bearings have relatively lowstiffness and damping, while aerodynamic bearings requirerelativelyhighmachiningaccuracyandassemblyerror.Althoughmagneticbearingshavetheadvantagesoflowvibration,quietness,andlowmaintenance,theycausemagnetic flux and need the material properties of the shaft tomeet their requirement. Moreover, they always need a stabi-lity control system. SFABs can effectively overcome frictionand wear during the start-up and shut-down process and ownhigh stability and controllability by operating the vibrationcomponent.Unfortunately,SFABsrequireabulkydeviceandhave high energy consumption and a short run time becausethe high-frequency vibration of the vibration generator in thesystemgeneratesheat.

2. Theoreticalmodeling

Governingequationbasedongasfilmlubricationtheory

Although a squeeze film levitation system is mainly com-posedofaradiantbodyandlevitatedobject,theestablishmentoftheoreticalmodelisverycomplicatedinreality.Thereasonlies in the levitated body's dynamic and the elastic defor-mationoftheradiantsurface,whichisusuallythemodal shape of the structure. Looking into the history of squeezefilmanalysis,wefoundthatthetheoreticalmodelhasevolvedfrom simple to complex (see figure 6). Due to the develop-mentofnumericalcalculationandanalysistools,theinfluenceofthelevitatedbody'sdynamicandtheelasticdeformation of theradiantsurfaceonthelevitationperformanceisgradually consideredinthemodel,leadingtoadeepeningunder-standingoftheworkingmechanismofsqueezefilmlevitation.

The state of the levitated object is one of the importantfactors to be considered in the establishment of a theoreticalmodel.Thetheoreticalmodel(Model1)inwhichthelevitatingobjectisfixedisusedbymanyresearchers

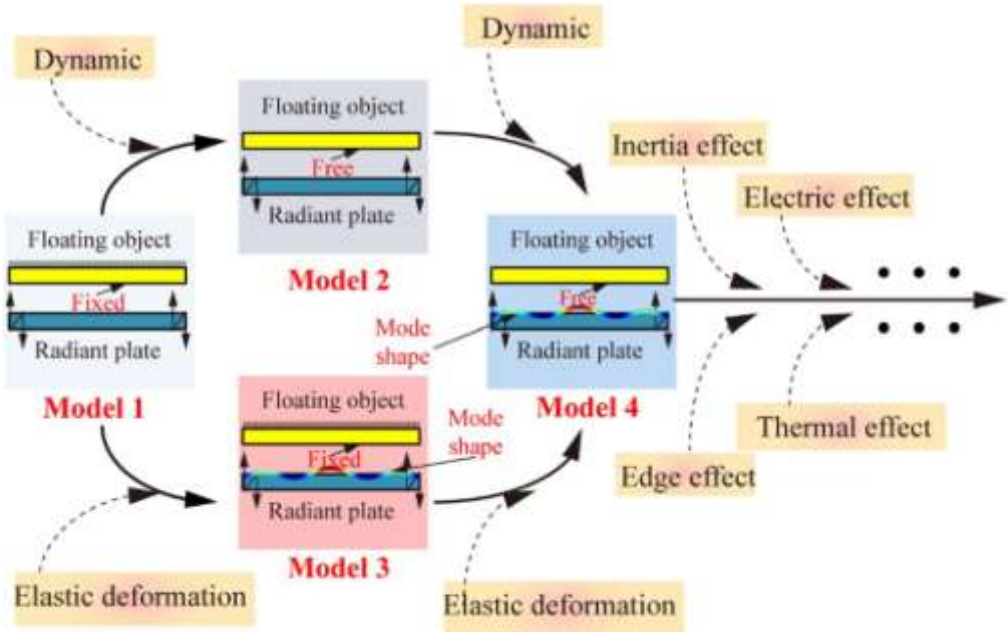

Figure 6.Gasfilmlubricationtheoryofsqueezefilmlevitation.

[13, 15, 70–72]. However, the assumption that a levitatingobject is fixed is not reasonable because the movement of thelevitatingobjectischangedintheactualsituation.Inorderto realize the squeeze levitation process more realistically, thedynamics of a levitating body are taken into account in thetheoreticalmodel(Model2)[73–76].

Anotherissuewiththetheoreticalmodelofsqueezefilms istheelasticdeformationoftheradiantsurface.Inthesqueezefilmlevitationsystem,abettersqueezeeffectcanbeobtained at resonance frequency. Note that the magnitude of the gasfilmclearanceisatthemicronlevel.Therefore,theinfluence ofthemodeshapeoftheradiantbodyonthesqueezefilm

leakage near the edges of the levitated object, was smaller byup to 50% compared to that of a one-dimensional analyticalsolution with the same boundary condition. Fenget al [90]introduced a grooving method into a squeeze film levitationsystemthatwasderivedfrombearingtechnology.Theyconcludedthatappropriategroovescanincreasethelevitationforce.

Based on the usual assumption of lubrication theory, theReynolds equation, which is a one-dimensional and time-dependent governing equation for pressure distribution in thesqueezefilm,canbeobtained[91]:

¶ ¶P ¶(PH)

effectcannotbeignored.

PH^3 =s ,

(1)

Theconditionsofmoreaccuratemodels(Models3and4)with themodeshapeofthe radiantbody considered which havebeenpresentedbymanyresearchers[77–81]arethe

where

p

¶X ¶X

h x

¶T

12mw L 2

subjectofstudybecausetheycomplywiththerealconditionsofsqueezefilmlevitation,particularlywhenworkingata

P= ,H=

P_a h_0

,X= ,T=wt,s=

L

P_a h_0

,

higherfrequency.Basedontheirtheoreticalmodels,thetheoreticalresultsshowgoodagreementwiththeexper-imentalresults.

A modified Reynolds equation considering the inertiaeffectsofsqueezefilmwaspresentedbyseveralinvestigators[82–85].Furthermore,NomuraandKamakura[86]developeda model that includes viscosity and acoustic energy leakage.Later,asimilarnumericalstudywasconductedbyMinikes et al [87] using a modified Reynolds equation. Minikes andBucher[88]developedatheoreticalmodelcouplingthe

whereP and H correspond to non-dimensional pressure andmean clearance normalized by ambient pressure (P_a) and gasfilm clearance (h_0), respectively. The dimensionless lateralcoordinateisrepresentedbyZ;airviscosityandangular velocity of vibration are denoted by m and w, respectively; Tis dimensionless time;is the time; L is the width of flatplane;andisthesqueezenumber.

Similarly,thetwo-dimensionalReynoldsequationcanbewrittenasfollows:

¶ ¶P ¶ ¶P ¶(PH)

dynamicsofasqueezefilmlevitatedmassandvibrating piezoelectricdisc.Moreover,MinikesandBucher[89]

PH^3 +

¶q ¶q

PH^3 =s ,

¶X ¶X ¶T

(2)

introduced the release boundary condition and the isothermalassumptions into a squeeze film levitation model through acomputational fluid dynamics scheme. It was found that thelevitationforce,whentakingintoconsiderationtheenergy
wherethedimensionlessaxialcoordinateandcircumferentialcoordinatearedenotedbyXandq,respectively. Equations(1)and(2)containonlythesqueezefilmeffect.Thetwo-dimensionalReynoldsequationcontaining

thesqueezefilmeffectandtheaerodynamiceffectcanbeexpressedasfollows:
aretwocrucialparametersforasqueezefilmlevitationsys-tem.Equation(6)isusuallyusedinthestudyofasqueeze

¶ ¶P ¶
¶P
¶(PH)
¶(PH)

filmlevitationsystemfortransportationorrotation.Its

PH3___ +
¶q ¶q
PH3___ = L
¶X ¶X ¶q
+s ,
¶T
(3)

validityhasbeenverifiedbytheinvestigatorsthrough experiments[99,100].Experimentalvaluesagreewellwiththeoreticalvaluesbasedonequation(6).
whereListhenumberofbearingsandisrepresentedby

6mW L 2

Furthermore,forasqueezefilmlevitationgeneratedby flexural vibration, the particle velocity amplitude distributioniswrittenas

L= P h ,
a 0

whereWreferstotherotationalspeedofrotor.
Thefirstright-handtermofequation(3)denotestheaerodynamiceffect,whichisgeneratedbythephysical

v(x,y,z)=1∬v̇(k_x,k_y)´exp[j(k_xx+k_yy 4
+k_zz)]dk_xdk_y.

(7)

wedge.Thesecondright-handtermofequation(3)reflects
Here,k^2+k^2+k^2=k^2=(w^2
c^2),k_x,k_y,and$k_z$arethe
thesqueezefilmeffectthatisgeneratedbythecyclically
x y z a
0a /
x,y,andzdirections,
squeezingactionoftheradiantbody.Theaerodynamiceffect,squeezefilmeffect,andhybrideffectsontherunningchar-
wavevectorcomponentsalongthe
respectively.Theradiationpressureofaplanewaveinthez
directioncanbeobtained:
acteristicsofthesqueezefilmbearingarediscussedin

section5.

p(k_x,k_y)=1+g 1+sin(2k_z h) áE_z(k_x,k_y)ñ
(8)
2 2k_zh

Governingequationbasedonacousticradiationpressuretheory

$\langle E_z(k_x,k_y)\rangle = \frac{\rho_a v^2(k_x,k_y)}{4\sin^2(kh)}$ (9)

.

The acoustic radiation pressure is the time-average pressureacting on a levitated object in a sound field, which was firstcomputedbyLoardRayleigh[92].Sincethen,many

Thus,thetotalradiationpressurecanbeexpressedasfollows[100]:

researchershavedevotedthemselvestothetheoryofacousticradiation pressure [93–96]. Even if there are some improve-mentstothetheoreticalresearch,thereisstillsomeconfusionand paradoxes in the theory of acoustic radiation pressure.Thelandmarkworkinwhichaformulationappliedtocal-culateRayleighradiationpressureinidealgasonaperfectly

$\Pi|_{z=h} = \iint_{k_x^2+k_y^2<k_a^2} p(k_x,k_y)\,dk_x dk_y.$ (10)

Comparison oftwotheories

reflectingtargetwascompletedbyChuandApfel[97].Later,the theory of acoustic radiation pressure was extended andgeneralizedbyLeeandWang[98].TheexpressionderivedbyChu and Apfel for Rayleigh radiation pressure is given asfollows:

Thetwomethodsmentionedabovehavetheirownchar-acteristics. The squeeze film levitation model based on gasfilmlubricationtheorycanbeusedtodescribepurelyviscousair in a gap. However, this method is limited to cases withextremely small levitation distances. The squeeze film levi-tationmodelestablishedbyacousticradiationpressuretheory

$p = \langle P - P_0\rangle = \frac{1+\gamma}{2}\left(1+\frac{\sin(2kh)}{2kh}\right)\langle E\rangle$ (4)

islimitedtocaseswherethegasviscosityisnegligible.Zhao etal[101]madeacomparativeanalysisofthetwomethodsto seetheirpredictionaccuracy.Theyfoundthatthesqueeze

$\langle E\rangle = \frac{\rho_0}{4}\left(\frac{a\,\omega_0}{\sin(kh)}\right)^2, \quad k = \frac{\omega}{c}$ (5)

filmlevitationmodelbasedongasfilmlubricationtheoryobtainedasatisfactoryfitforsmallgapdistances,butthe

where⟨⟩standsfortimeaveragedvalues,γ,h,k,a_0,ρ_0,ω_0, andarethespecificheatratioofthemedium,distance between two surfaces, wave number, vibration amplitude,density of the medium, angular velocity of the wave, andspeed of sound, respectively. The energy density is repre-sentedbyE.

When the levitation distance is in the micrometer range,itismuchsmallerthanthesoundwavelengthinthefreefield.Therefore, equation (4) can be simplified to a linear equationforradiationpressureinthefollowingform:

modelbasedonacousticradiationpressuretheorygotasatisfactory fit for a relatively large distance. When the levi-tation distance increases to a certain extent, the two methodsfailto agreewiththemeasured values. In 2016, Melikhovet al [102] developed a theoretical model, including the vis-cous and acoustic effects, which can be applied for a widerangeoflevitationheights.

3. DifferenttypesofSFABs

i = 1+g
4
a2
r0c20,
h2
(6)

Becauseoftheadvantagesmentionedabove,SFABswithdifferentfunctionshavebeenproposedbyinvestigators,such

wheresin(kh) »khisassumed.Fromequation(6),itcanbeconcludedthatthevibrationamplitudeandlevitationdistance assqueezefilmairlinearbearings,squeezefilmthrustbear-ings,andsqueezefilmsphericalbearings.

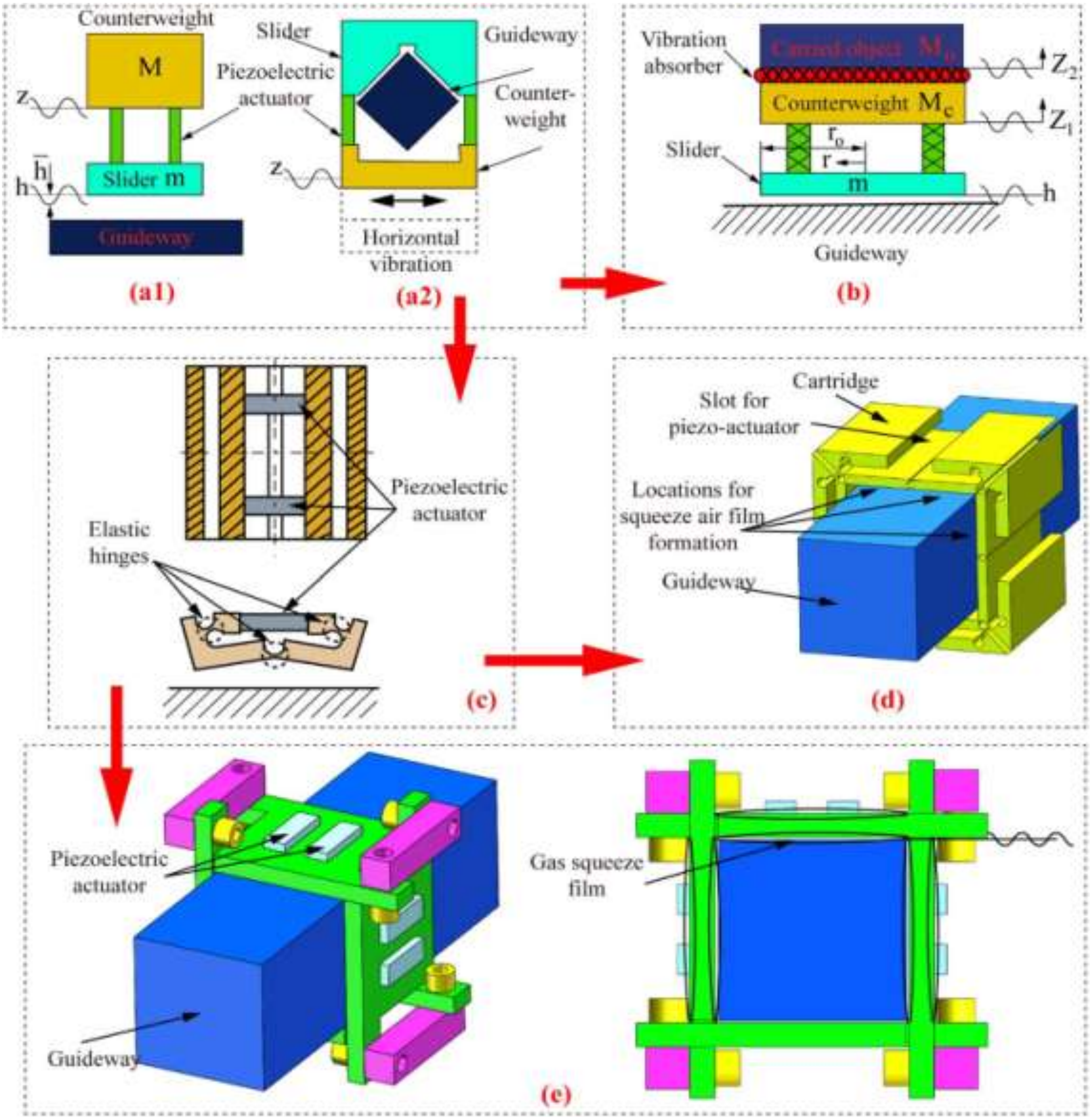

Figure7.Schematicdiagramofsqueezefilmairlinearbearing:(a)YoshimotoandAnno[103],(b)Yoshimoto[104],(c)Yoshimotoetal[74],(d)StolarskiandChai[105],and(e)Yoshimotoetal[78].(a)Reproducedwithpermissionfrom[103].(b)Reproducedwithpermissionfrom [104].Copyright© 1997 by theAmericanSociety

ofMechanicalEngineers.(c)Reproducedwithpermissionfrom[74].© TheJapanSocietyofMechanicalEngineers.(d)Reprintedfrom[105],Copyright(2006),withpermissionfromElsevier.(e)Reprintedfrom[78],Copyright(2007),withpermissionfromElsevier.

Squeezefilmairlinearbearings

Yoshimoto and Anno [103] proposed a rectangular squeeze filmairgasbearingwithacounterweight,asshowninfigure7(a1).The proposed bearing consists of a slider and counterweight,whichareconnectedtogetherbypiezoelectricelements.Squeeze filmpressurewasgeneratedbetweenthesurfaceofthesliderandguideway.Furthermore,theauthorsdesignedanewbearing

guideway system based on the proposed bearing for a linearmotionguide(seefigure7(a2)).Experimentswereperformedtosuccessfullyinvestigatethefloatingcharacteristicsofthe bearing.Stablelevitationofacounterweightofabout0.4kglevitatedby thebearingwith450mm^{2}wasachieved.However,thelevitatedobject oscillated together with the counterweight, which was detrimentaltothemotionaccuracyofthelevitatedobject.

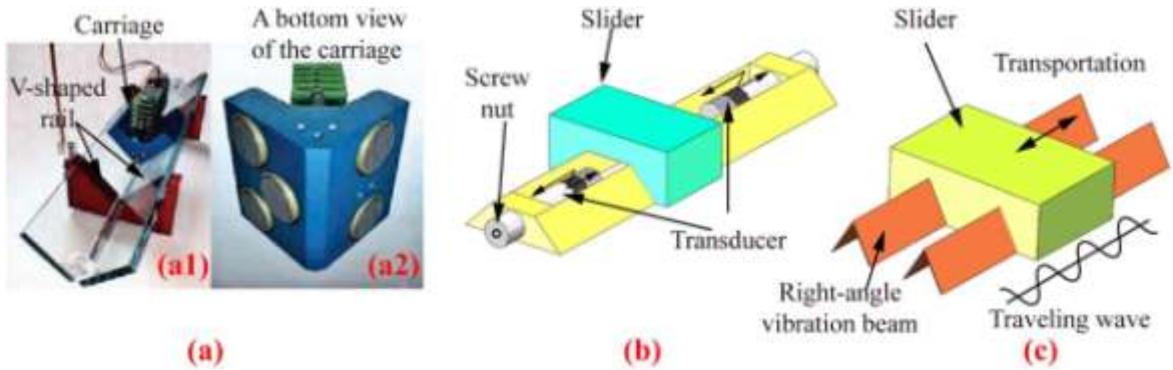

Figure8.Schematicdiagramoflinearsliderbearing:(a)Wiesendanger[106],(b)Ideetal[107],and(c)Ideetal[108].(a)Reproducedwithpermissionfrom[106].(b)Reproducedfrom[107].Copyright©2005TheJapanSocietyofAppliedPhysics.Allrightsreserved.
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Tosolvethisproblem,anewsqueezefilmgasbearingwithavibrationabsorber,whichcanbeusedtoreducethevibrationamplitudeofthelevitatedobjectandimprovethemotionacc-uracy, was proposed in [104]. As shown in figure 7(b), avibrationabsorbermadeofsiliconerubberwasinsertedbetween thecounterweightandthecarriedobject.Numericalandexperimental results showed that the absorber was effective inreducingthe vibration amplitude of the carriedobject.

Later,anewtypeofsqueezefilmgasbearingwithelastichingesforlinearmotionguidesystemswasproposedbyYoshimoto et al [74], as shown in figure 7(c). The bearingconsists of three elastic hinges and two piezoelectric actua-tors,whichproducesagreateramplitudethantheprevious bearing proposed in [103] due to the use of elastic hinges.Meanwhile,thisbearingincreaseditsminiaturizationbecausea counterweight and a horizontal fixing mode of the piezo-electricactuatorswereused.

Following the research of Yoshimoto on bearings withelastichinges,StolarskiandChai[105]proposedanovellinearmotion sliding bearing using elastic hinges. The profile of thelinear motion sliding is shown in figure 7(d). The proposedbearingconsistsofaspeciallyshapedcartridgewhichcanbe convenientlydividedintoeightidenticalparts.Fouractuatorsaremountedoneachslotforgeneratingasqueezefilmeffectatfour converging gaps between the cartridge and the guideway. Thestructureoftheproposedbearingissimilartothedesignin figure7(c).However,thedifferenceisthattherearefourslotsforinstalling piezoelectric actuators rather than two. For the bearingproposed in figure 7(c), noise will be generated during operationduetothelowfrequencyofoperation.Inordertosolvethis problem,anewsquareSFABoperatedintheultrasonicregimeto avoid the generation of noise was presented in [78] (seefigure7(e)).Theproposedbearingconsistsoffourplateswhicharemountedbyascrew.Notethatonlypiezoelectricactuators aremountedonthetopandtwosides.Thus,theuppergasfilmpressure is the main power to produce the load-carrying capa-city. However, the gas film pressure on the two sides onlymaintains the horizontal position of the slider. Experimentalresults show that the load-carrying capacity of 10 N is achieved,inthecaseofanaveragefilmthicknessof5μm.

A linear slider bearing using disc-shaped piezoelectricbendingelementswasproposed[106].Thelinearsliderbearing consistsofaV-shapedrailmadeoftwoglassplatesandacar-riage (see figures 8(a1) and (a2)). The opening angle of the rail issetto90degrees,andthefivebearingmodulesaremountedonthe carriage. A total load-carrying capacity of 30 N was obtainedwhendrivenat24volts.

After that, Ide et al [107] proposed a new low-profiledesignusingtwoflatbeamsexcitedbytwoLangevintrans-ducers for a linear bearing, as shown in figure 8(b). Two flatlongbeamsconnectedtotwo'+' -shapedvibrationcon-verterswithscrewswereusedasaguiderail.Theangleofthe two output surfaces of the vibration converter was set to 45degrees.ALangevintransducerexcitedbyatwo-phasesinusoidal voltage source was used to drive the beams. Aslider was levitated by the squeeze gas film generated bybendingvibrations excitedalong thebeams. Forthisbearing, a further study was conducted by Koyama et al [109]. Thelevitationforce(4.8 kN m^{-2})andthelevitationrigidity(2.5kN$mm^{-1}m^{-2}$)weremeasuredforalevitationdistanceof 2.2μm.Themaximumthrustandthetransportationspeed werealsomeasuredtobe1.3mNand34.6mms^{-1},respec-tively,foracaseoftheslider'sweightof107g.In[108],alinearbearingconsistingofapairofright-anglebeamsandLangevintransducerswasdesigned(referencefigure8(c)).TheLangevintransducersweremountedont heendofthebeambyascrew,whichcanbeusedtoexciteandabsorbultrasonicflexuralvibrations,forming a flexural travelingwavealongthe□-cross-sectionedbeam.Atransportation speedof 138mms^{-1} ofa90gslidersupportedbyright-anglebeamswasobtained.

The design and testing of a linear rectangular air bearingusing squeeze film generated by ultrasonic oscillation wasperformed in as described in [110]. The main structure of theproposedbearingwasahornconsistingoftwodirectional converters,showninfigure9(a),whichtransmittedtheoscillationsofthetwoactuatorstoeightbearingsurfaces.The squeeze film generated between the surface of the bearingsandthesurface ofthecarriage(seefigure9(b))canbeusedtolift and guide the carriage. Experiments were conducted on atestrigtoinvestigatetheperformanceofthebearing.The 0.18 μm p–p of the vertical straightness error was obtained intheexperiments.

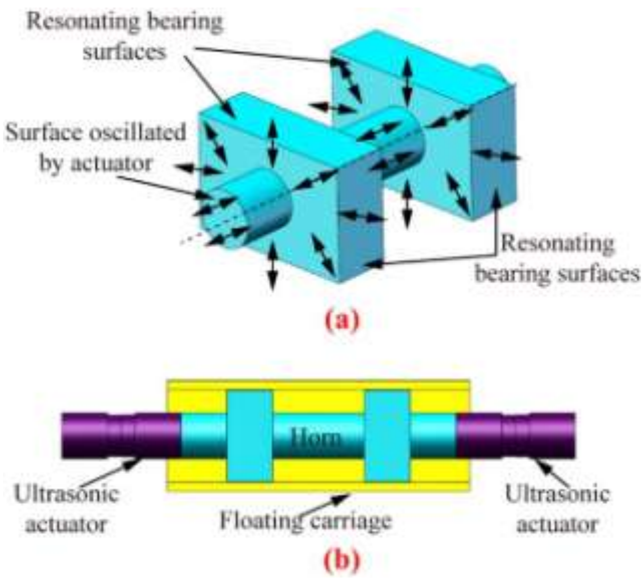


Figure 9.Schematic diagram of linear rectangular air bearing: OiwaandSuzuki[110].Reprintedfrom[110],withthepermissionofAIPPublishing.

Squeezefilmthrust bearings

A squeeze thrust bearing was produced between two paral-lel,coaxial,flatdisks,one ofwhich wasarotorwith flatdisks and the other was driven sinusoidally in a directionnormal to the surface [15]. A flat disk squeeze film bearingthat utilizes air films generated by ultrasonic oscillation wasreportedin[73].Similarly,theproposedbearingcontainstwo parallel and coaxial flat disks. The upper disk is levi-tated by the levitation force generated by a high frequencysqueezing motion of the lower plate driven by a piezoelectricceramiccylinder.

In[111],anultrasonicthrustbearingcomposedofa surfacepulleyandradiationsurfaceofthepiezoelectrictransducer was proposed. The surface of the piezoelectrictransducercanbeuseddirectlyasthebearingsurface.Squeezegasfilmgeneratedbytheultrasonicvibrationo fthe piezoelectrictransducerwasusedtosupporttheweightoftheshaft and the axial load (see figure 10(a1)). An ultrasonicthrust bearing and experimental device were manufactured.Experimentalresultsshowedthatultrasonicthrustbearinghas better levitation and antifriction performance than a slidingbearingandnon-liquidfrictionrollingbearing.

Songetal[112]developedanovelultrasonicthrustbearingwhichwasanimprovementoverthepreviousbearingdescribedin[111].Theradiationsurfaceofthepiezoelectrictransducerwasdesignedasaconicalstructureanddifferentfromthesurfaceofthecylindricalstructurewiththecircularplanarintheprevious bearing (see figures 10(a2) and (b)). Moreover, the radiationpressuregeneratedbythesurfaceoftheconicalstructurecan carry radial and axial loads simultaneously. Experimental resultsindicated that the proposed ultrasonic thrust bearing was moresuitableforhighspeedworkenvironments.

Squeeze film spherical bearings

A novel spherical squeeze bearing based on NFAL is pre-sented in [15]. The piezoelectric cylinder oscillates in a highfrequency,whichcausesthesockettooscillate.Thus,asqueeze film is produced in the gap that makes the ball floatfreely.In[72],asphericalsqueezefilmbearingwasdesigned.The proposed bearing consists of a hemisphere and a bearingshell, which are made of duralumin. When the bearing isworking, the second mode of the bearing shell is excited. In[113],atransducerwithaconcavesphericalsurfacewhich can be used to levitate a ball was designed (see figure 11).Theappropriateconcavesphericalradiatingsurfaceofthe proposed transducer was determined by the finite elementparametric method. The levitation height and levitation per-turbationoftheballwereinvestigated.Theexperimentsrevealed that the maximum levitation height and minimumlevitation perturbation were obtained when the radius of thelevitated ball was similar to that of the concave sphericalradiatingsurface.

A transducer which can be used to suspend high-massrotors was designed in [114] (see figure 12). The horn on thetopofthetransducerhasaconcavesurfacewhichcanbeusedto suspend spherical rotors with a diameter of about 40 mm.Experimentalresultsindicatedthataspereweighing1kg was successfully suspended. For the NFAL, the attenuationmotion of spherical rotors was further investigated in [115].The experiment’s results revealed that the maximum rotatingspeed and duration time of the spherical rotor were 6000 rpmand15min,respectively.

In [116], the authors describe a novel spherical bearingusingabowl-shapednon-contactultrasonicmotorwithahollowbowl-shapedsurfacethatcanbeusedtoproduceacoustic levitation force for a spherical object (see figure 13).Apiezoceramicringdividedintotwogroupswasusedto excitethestator.Whentwohigh-frequencyACvoltageswitha temporal phase shift of 90 were applied to the piezoceramicring, a traveling wave was produced in the spherical surfaceof the stator, resulting in a load-carrying squeeze film whichcan levitate or even directly drive a spherical rotor to rotatewithoutcontact.Amaximumrotatingspeedofabout1071 rpmwasobtainedfortheproposedsphericalbearing.Experimental results indicated that the proposed bearing haspotentialapplicationforsuspendedgyro.

4. HybridSFABs

CharacteristicsofhybridSFABs

In high-speed applications, the aerodynamic effect as well asthe squeeze film effect are included in the operation process.Thus,SFABscanbeclassifiedintotwotypes,namely, SFABs (only squeeze film effect) and hybrid SFABs (com-binedsqueezefilmeffectandaerodynamiceffect).Theschematicdiagraminfigure14representstheparameterstatus ofhybridSFABsandtheiroperatingprinciples.Thethree

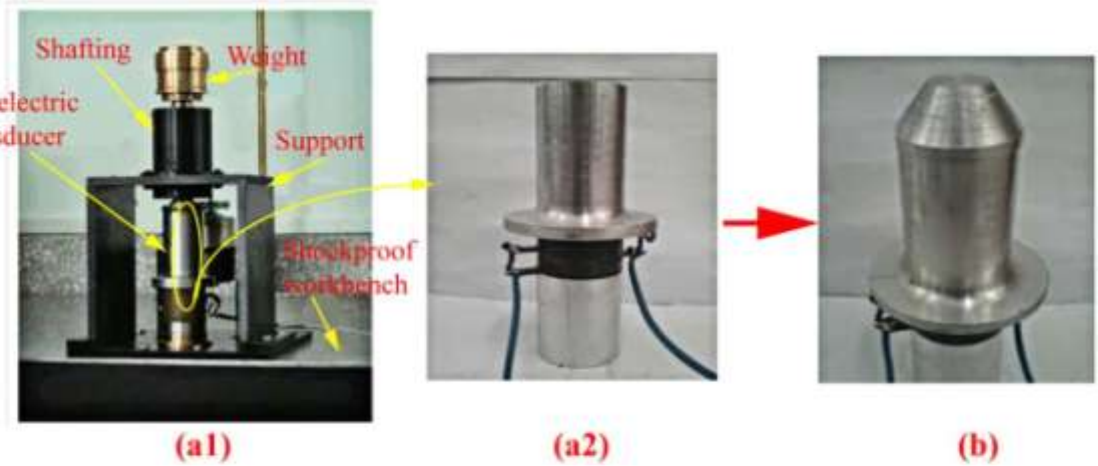


Figure10.Photographofultrasonicsuspensionthrustbearingandpiezoelectrictransducers:(a)Shijuetal[111],and(b)Songetal[112].
(a)©2015IEEE.Reprinted,withpermission,from[111].(b)Reproducedwithpermissionfrom[112].

Figure 11.Photographofthe transducerwithconcavesphericalsurface: Liuetal[113]. [113]© TheKoreanSociety ofMechanicalEngineersandSpringer-VerlagBerlinHeidelberg2013.WithpermissionofSpringer.

vertical dotted lines divide the schematic diagram into threeworkingareas.
The levitation force generated by the squeeze film effectinRegionIcaneffectivelysupporttherotor.Whenthelevitation force on the rotor is larger than the gravity of therotor, the bearing can overcome the wear during start-up.Thus,comparedwithaconventionalnon-contactaero-dynamic bearing, the service life of a hybrid SFAB can begreatlyimproved.

In Region II, when the rotor begins to rotate, the aero-dynamiceffectgetstoworkduetotherelativespeedbetweenthe rotor and bearing surface. The levitation force producedby squeeze film effect and aerodynamic effect supports therotor, simultaneously. The aerodynamic effect increases withthe increase in rotating speed, which leads to an increase inload-carrying capacity. Afterwards, the rotor speed graduallyreaches a constant value in Region III. In this region, thespeed remains constant; and the input voltage can be selectedaccordingtotheworkingconditions.Theload-carryingcapacity produced by hybrid SFABs results in a higher valuethan that produced by conventional aerodynamic bearings atthe same speed due to the squeeze film effect enhancing theload-carrying capacity. Throughout the three steps, the rotorislevitatedstablyandtherunningperformanceofthebearingcan be controlled by adjusting the input signal to vibrationgenerator.Inaddition,itmustbeemphasizedthattheworkingmode of SFABs should be combined according to the actualworkingneeds.

ThemainfeaturesofhybridSFABsarelistedanddescribedasfollows:

- Nodryfrictionandwearduringthestart-upandshutdownstages.

When the levitation force produced by the squeezefilm effect is large enough, the rotor can be effectivelysupported.Therefore,comparedwiththetraditionalaerodynamicbearing,theSFABcan effectivelyavoidthe friction and wear caused by the start-up and stopstages.

- Enhancedload-carryingcapacity.

Load-carryingcapacity of hybrid SFABs is enhanced by introducing the squeeze film effect into theaerodynamiceffect,especiallyinlargeeccentricity.

- Goodstabilitywiththehelpofthesqueezefilmeffect.

Atraditionalaerodynamicbearingwilllosestability ataspecificspeedduetoitscross-coupledstiffness.However, the force generated by the squeeze film effectwillsuppresstherotorvibrationandimprovethestability.

- Activecontrollability.

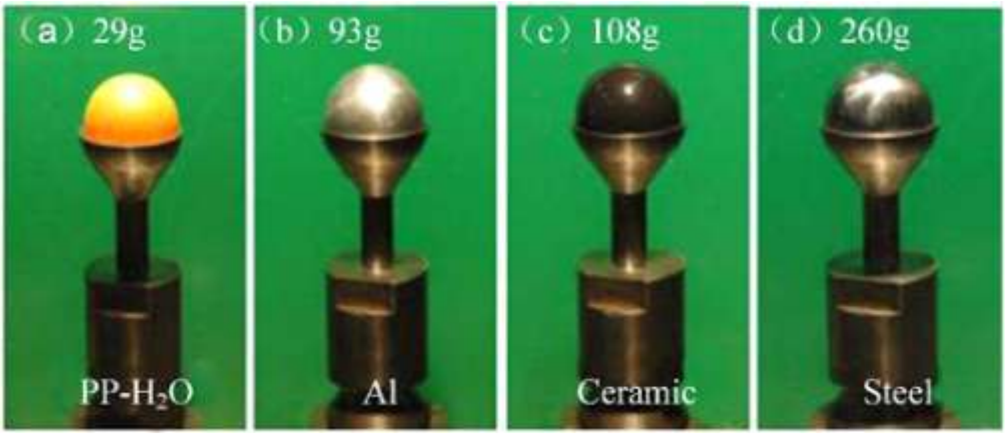


Figure12.Photographsofdifferentsphericalrotorsbeinglevitated:Hongetal[114].Reprintedfrom[114],withthepermissionofAIPPublishing.

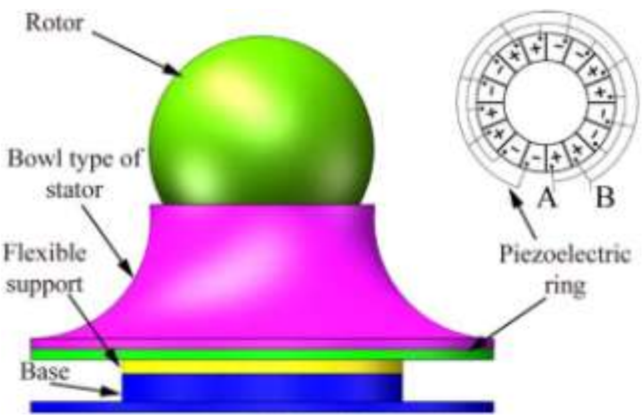


Figure13.Schematicdiagramofnon-contactsphericalbearing:Chenetal[116].Reproducedwithpermissionfrom[116].

without friction, while squeeze film B played a supportingrole in the strain-producing tube. In addition, the squeezemotionparalleltotheaxisproducedsqueezefilmatbothendsofthestrain-producingtube.Therefore,thesqueezefilmbearing could provide both a radial support force and axialsupport force. In [118], a piezoelectric oscillating bearingsupported by a pair of contiguous discs was developed. Twodisks produced the opposite strain along the axis. In otherwords,oneproducedexpansionandtheotherproducedcontraction.Therefore,arelativelylargeamplitudeofmotionwas imparted to the bearing as there was no relative motionbetweenthefacingsurfacesofthetwodiscs.

Hu etal[119] designedand fabricatedanultrasonicbearingprototypewhichwasactuatedbytwoLangevintransducersdrivenbytwoACvoltageswithaphasediffer-enceof90□,asshowninfigure16.ThetwoLangevin

The stable position of the rotor can be controlled byadjusting the vibration of the actuator and the levitation forcefromthesqueezefilmeffect.

DifferenttypesofhybridSFABs

Salbu[15]proposedahybridsqueezefilmairjournalbearingwiththejournalsqueezefilmeffectandsqueezethrusteffect.

Levitation forces were generated by high frequency move-ment of the piezoelectric cylinders and the flat piezoelectricdisk. Later, a cylindrical squeeze-film journal bearing with aradiallypoledpiezoelectricsleevewhichprovidedradialsqueeze film motion was proposed [17]. In this bearing, adouble layer squeeze film was formed on the inner and outersurfaces of the sleeve-type transducer. Farronet al [117]proposeda novelSFAB which mainly consistedofa rotating member,strainproducingtube,andsupportframe(seefigure 15). The heart of the bearing was a strain producingtube,whichcouldproducehighfrequencyandlowamplitude motion in directions both parallel and perpendicular to theaxis of the rotating member. A double layer of squeeze filmcould be produced by squeeze motion perpendicular to theaxis, which was squeeze film in Gap A and squeeze film inGapB.SqueezefilmAallowedtherotatingmembertorotate

transducers were bolted on the stator with a distance of threequarters of wavelength. A traveling wave, which was used todrive the rotor rotation, was generated in the surface of thestator. Therefore, the radial support and rotation of the rotorcould be realized by the force generated by the travelingsoundfield.

An active squeeze air bearing based on ultrasonic oscil-lationwasproposedin[120],asshowninfigure17.Adirectional converter was used by the bearing to transmit theoscillation of Langevin transducer to both an end surface anda side surface. In other words, the converter could generateradialandaxialsqueezemotion,respectively.Atestrig,which consisted of a bolt-clamped Langevin transducer, arotor, and a directional converter, was built to investigate themotion error compensation characteristic of the bearing. Themovement of a master ball supported by the rotor was mea-sured by a fiber optic displacement sensor. This PI feedbackcontrol with compensation provided lower axial runout thanPIfeedbackcontrolwithoutcompensation.

An aerodynamic bearing with adjustable geometry, asshown in figure 18(a), was studied [77]. The shape of theinnersurfaceofthebearingcouldbechangedfrominitial cylindrical to three-lobed due to the use of elastic hinges. Sixpiezoelectricactuatorswereinstalledinthreeslotsevenly

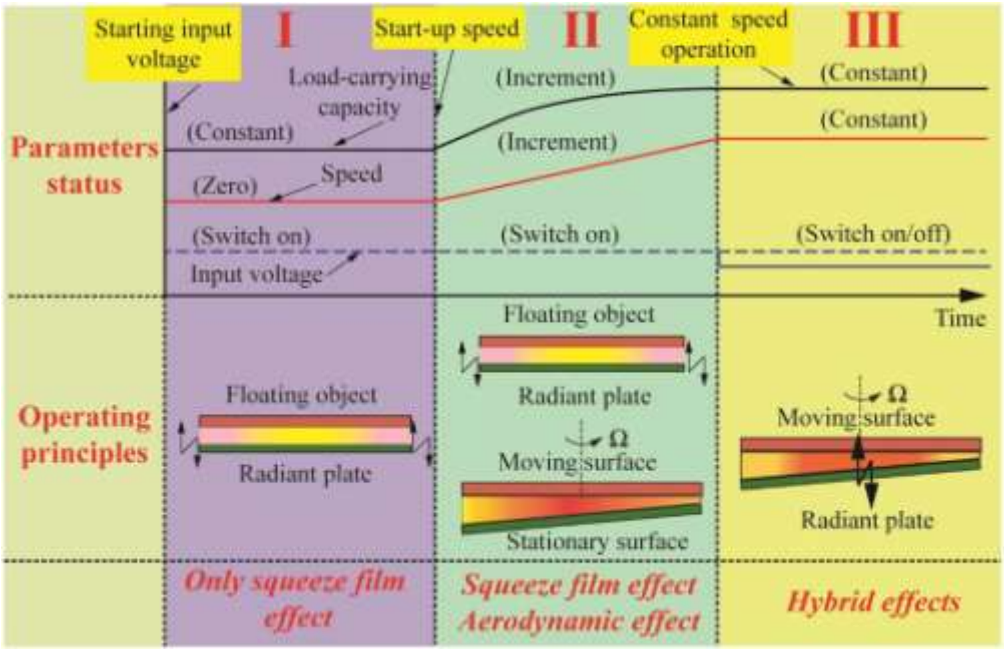
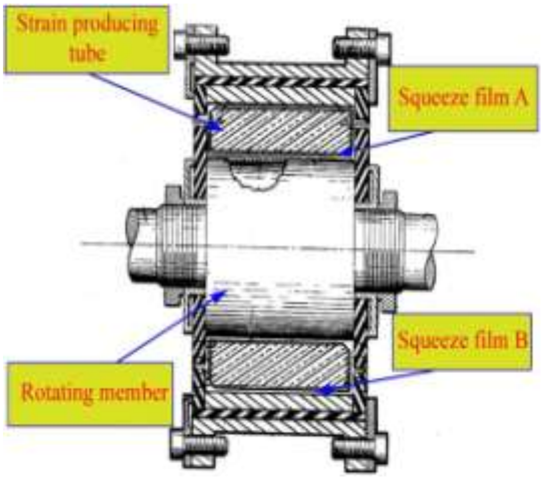


Figure14.Schematicdiagramofoperatingstepsofhybridsqueezefilmairbearings.



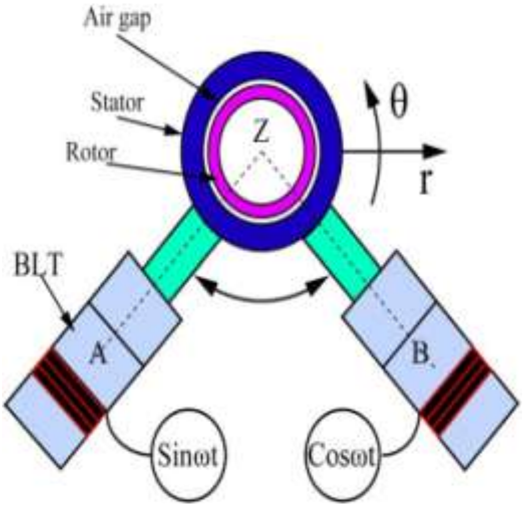


Figure15.Bearingstructureassemblyschematic:Farronetal[117].

Reproducedwithpermissionfrom[117]. Figure16.Schematicdiagramofultrasonicbearing:Huetal[119]. Reprintedfrom[119],Copyright(1997),withpermissionfrom distributed around the circle. Piezoelectric actuators periodi-cally squeezed the gap between the bearing and the rotor,forming a layer of gas film pressure, and the rotor was sus-pended.In2011,Stolarski[122]experimentallyandnumerically investigated the dynamic characteristics of thebearing. Comparing the theoretical and experimental results,itwasfoundthatthesqueezefilmeffectgeneratedbysqueezemotioncouldsignificantlyextendthethresholdspeed ofinstability. Later, the systematic analysis of the levitationmechanism and stability of the bearing at a higher operatingfrequencywascarriedoutbyFengetal[123].In[121],the authorspresentedasimilarbearing with [77] (seefigure 18(b)). The influence of the squeeze film effect on therunningperformanceoftherotortothisbearingwasstudied byStolarskiet al [124]. Experimental results showed that thesqueezefilmeffecthadanobviouseffectonreducingrotor

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vibration.Itwasnoticedthatataconstantrunningspeed(20 000 rpm) and external load (0.31 N), the shaft vibrationswerereducedbyapproximately37.5%and42%inthexandydirections,respectively.

In [125], three different types of air journal bearingsutilizingNFALweredesignedfromtheperspectiveofasimplified structure and elastic bore deformation (see figure19).Theresonancefrequencyandvibrationmodewere determinedusingANSYS.Thesqueezefilmloadcapacityof these bearings was tested through a specially built test rig.Theoretical and experimental results showed that a journalbearing using acoustic levitation is feasible and has potentialapplications,especiallyforlightloads,cleanliness,andcompactnessrequirements.Furthermore,they concluded that

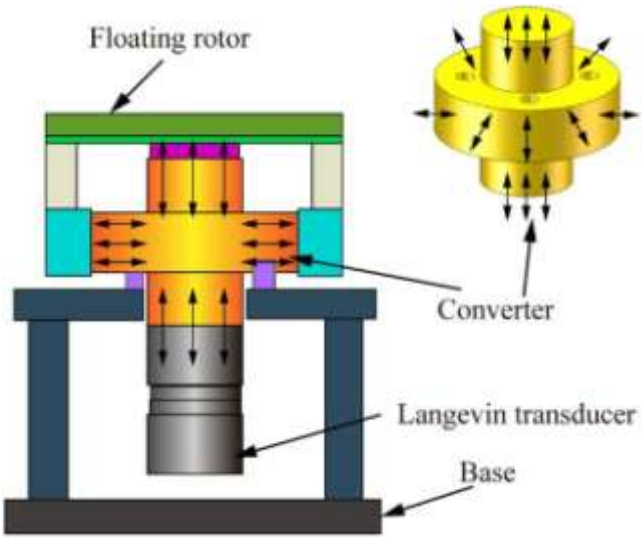

Figure17.Schematicdiagramofactivesqueezefilmbearing:OiwaandKato[120].Reprintedfrom[120],withthepermissionofAIPPublishing.

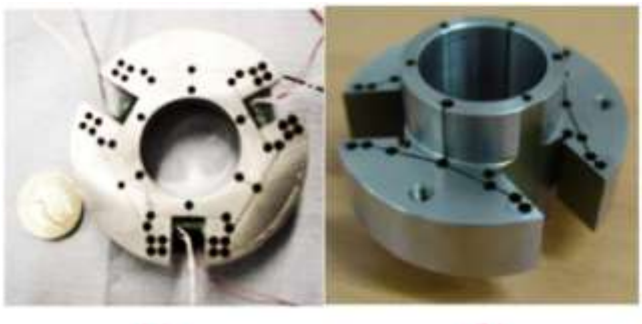

Figure18.Photographs ofacoustic bearing: Stolarskiet al[77, 121].
(a)Reproducedwithpermissionfrom[77].(b)Reprintedfrom[121],Copyright(2015),withpermissionfromElsevier.

thebearingofDesign3showedbettercharacteristics.Therefore, the running performance of the bearing of Design3 was studied by Shouet al [126]. The experimental resultsshowed that for a given external load, the threshold speed ofthebearingrunningwithoutthesqueezefilmeffectwas5000 rpm while the threshold speed for the bearing operatingwiththesqueezefilmeffectwas20 000 rpm.Clearly,thesqueezefilmeffectcansignificantlycontributetothedynamicstability of an aerodynamic bearing, especially for lightlyloaded, gas-lubricated bearings. Later, a SFAB similartoDesign 1 in [125] was proposed [127]. The proposed journalbearingequippedwiththree20 mmlonglongitudinalfinsrequirestheuseofsixpiezoelectricactuatorsarrangedaroundthecircumferenceoftheoutersurfaceofthebearing.

In 2013, a SFAB with high load-carrying capacity withtheabilityofprecisionspindlepositioncontrolwaspresentedin[101](seefigure20).Thebearingconsistedmainlyofthree Langevin-typetransducerswhichwerespeciallydesignedand fabricated.Threetransducers,eachcovered100°ofacylindrical surface, were positioned 120° apart on a housing.Thespindlewassupportedbythearcedconcaveradiation surface of the three transducers which were driven in the firstlongitudinal mode. It was noticed that each radiation surfacewas an independent vibration surface. The position trajectoryofthespindlecouldbecontrolledbymodulatingthevibrationamplitude of the corresponding transducer. The maximumload-carryingcapacity of51 N wasobtained,and a positionaccuracy of the spindle center was achieved in the range of100 nm. The simulation and experimental results showed thatthe proposed squeeze film journal bearing could be used forultra-precisionmachiningprocesses.

Wangetal[128]proposedanultrasonicbearingwithlevitationandpositionfunctions.Thebearingconsistedofabearinghousing,avibratingcylindricalstator,andtwocir-cularplates,asshowninfigure21.Acousticlevitationforcewhichprovidedradialnon-contactsupportfortherotorwasproducedbypiezoelectricactuatorssqueezedonthecylind-ricalstatorsurface.Thesupportintheaxialpositionwasprovidedbytheforceformedbythesqueezingvibrationofthecircularplates.Theproposedultrasonicbearingthatwasabletolevitatearotorweighed1.2Nandhadpotentialapplicationvaluesforthesupportofthehighprecisiongyros.Anultrasoniclevitatingbearingexcitedbythreepiezo-electric transducers was developed as described in [129], andshowninfigure22.Onedistinctpropertythatdistinguishedtheproposedbearingfromapreviousbearing,describedin [101],wasthatthebearinghadtheabilitytoself-alignandcarryradialandaxialloadssimultaneouslyduetotheproperdesignoftransducerstructure.Amaximumradialloadof15Nandanaxiallevitatingloadof6Nwereobtainedfromtheestablishedtestsystem.Theoreticalandexperimentalresultsshowedthattheproposedbearingprovidedabettermethodforbidirectionalsupportingcapacity.Later,thefric-tioncharacteristicsandrunningstabilityofthebearingwerestudied,asdescribedin[130,131].Thefrictiontorqueincreasedwithanincreaseinrotationalspeed,andtorqueoflessthan120mNmwasobtainedat20000rpm.Inaddition,experimentalresultsshowedthattheultrasonicbearingcould runstablyinthespeed-downandspeed-upprocesses.

Fenget al [132] presented a novel SFAB with flexurepivot-tiltingpads,asshowninfigure23.Thepadswereconnectedtothebearinghousingthroughastraightbeamandflexural web. The radical force was generated by squeezingthe gas between the pads and rotor periodically using piezo-electric actuators. This bearing had two distinct advantages,which were different from previous squeeze film bearings.First, the bearing always adapted well to squeeze actions.Second, the proposed bearing had a better stability when thebearingworkedathighspeedduetolowcross-coupledstiffness.Numericalandtheoreticalresultsshowedthatitwasfeasible for the proposed bearing to support high-speed andhigh-precisionshafts.Shietal[133]theoreticallyandexperimentallyidentifiedtheinfluencesofmaterialchar-acteristicsonthelevitationperformanceofsqueezefilmbearing.Theselectionofsqueezefilmbearingmaterialcharacteristicsisimportantforthelevitationperformance.

Thetestbearingsthatwerecomprisedoftwodifferentmaterials(AL2024 and60Si2Mn) hadsimilarresonancefrequencyanddifferentvibrationamplitudesgeneratedbythe

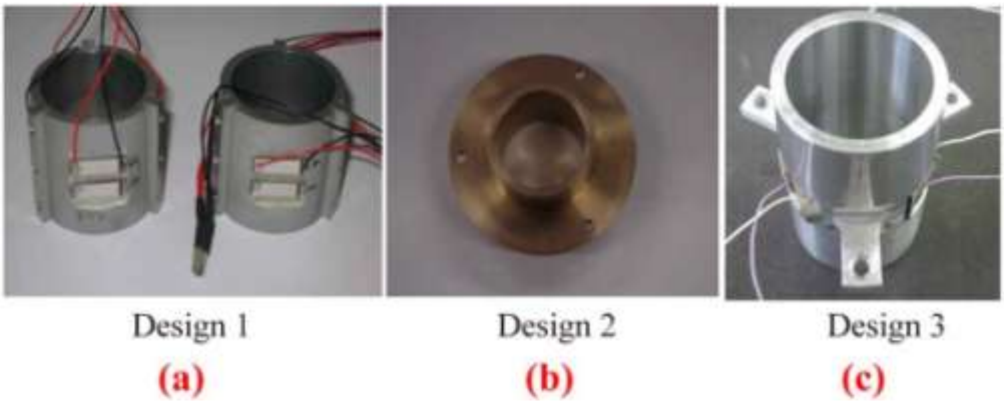

Figure19.PhotographsofairjournalbearingusingNFAL:Stolarskietal[125].Reproducedwithpermissionfrom[125].

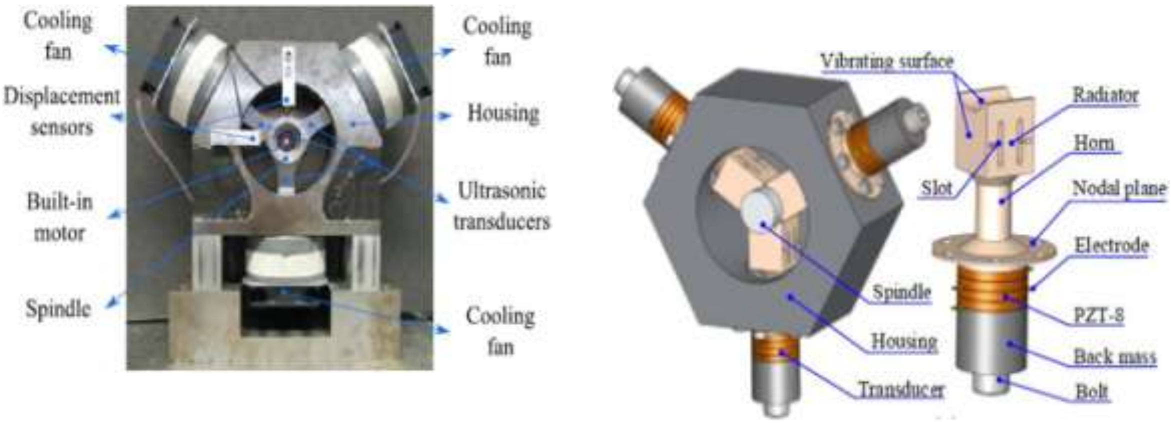

Figure 20.Photograph of ultrasonic levitation journal bearing: Zhaoetal[101].Reprintedfrom[101],Copyright(2013),withpermissionfromElsevier.

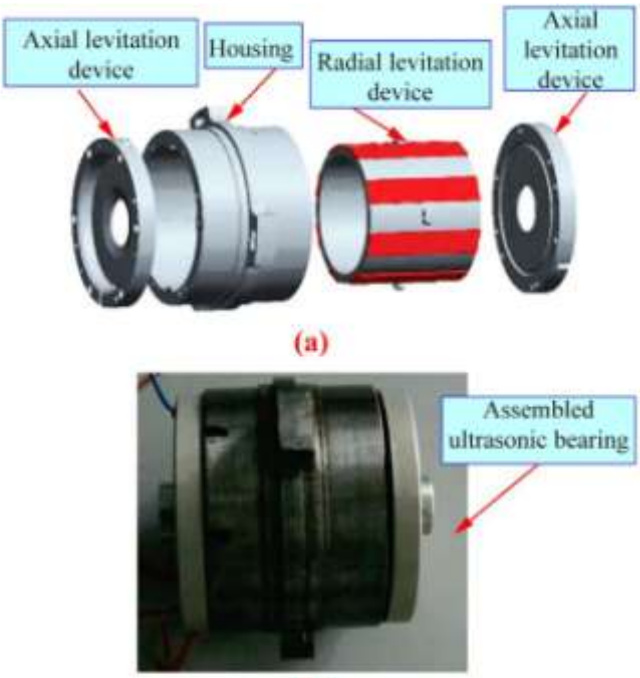

Figure 21.Explodedview and assemblingdrawingofultrasoniclevitationbearing:Wangetal[128].©2013IEEE.Reprinted,withpermission,from[128].

Figure 22.Schematicdiagramofultrasoniclevitationbearing:Li etal[129].Reproducedfrom[129].CCBY4.0.

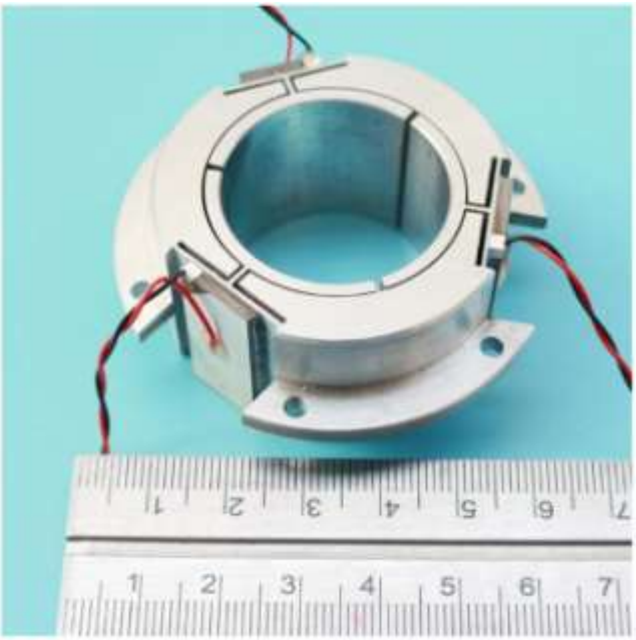

Figure 23.Photograph of squeeze film air bearing: Fenget al [132].Reprinted from [132],Copyright(2017),with permission from Elsevier.

sameinputvoltage.Therefore,resonancefrequencyandvibration amplitude were also concluded to be two crucialpartsforSFAB.However,thevibrationamplitudewasamore

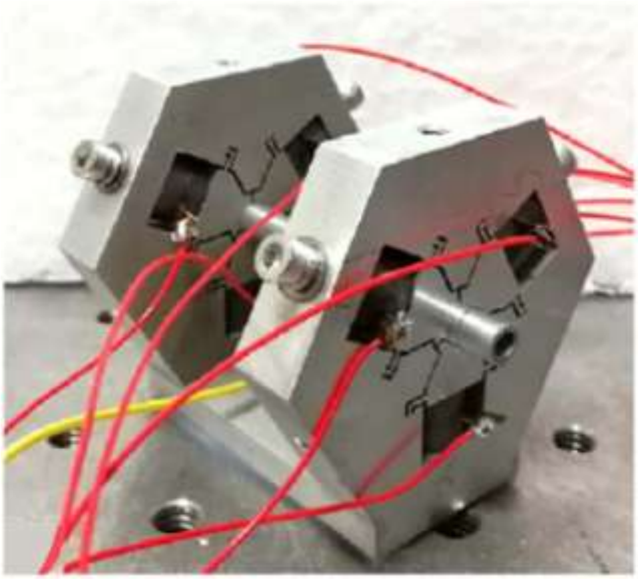

Figure24.Photographofnon-contactjournalbearing:GuoandCao[135].Reprintedfrom[135],Copyright(2018),withpermissionfromElsevier.

importantpartthanwasresonancefrequency.Theconclusionwasabetteranswertothequestionraisedbythelitera-ture[134].

An active non-contact journal bearing with bidirectionaldrivingcapabilityachievedbyusingcoupledresonantvibration was proposed in [135]. The design of the bearingconsistedofthreeidenticalhornstructureswithaconcaveend surface(referencefigure24).Themainfeatureofthisbearing,whichwasdifferentfromthepreviousultrasonicbearing,was that it adopted the couple mode shapes, i.e. first longitudinalmode and second bending mode. The alternating work of thelongitudinalandbendingmodeswillresultinellipticalvibrationoftheconcaveendsurface.Therefore,verticallevitationandlateraldrivingforcewereproduced,whichsupported and rotated the rotor, respectively. It was noticedthat the lateral driving force was different from the travelingwave and viscous shear force as it was mainly produced bythetangentialcomponentofthesqueezefilmpressure.Experimentalresultsshowedthattherotationalspeedof 555rpmcouldbeobtainedbyadjustingtheinputphase angle.

Discussion and futuretrends

The squeeze film effect has been demonstrated to be capableof levitating objects for a wide range of applications. One ofthe main issues is the influence of governing parameters onthe levitation performance and, in particular, the load-carryingcapacity. In general, the SFAB system consists of bearing,vibration generators, which are usually piezoelectric trans-ducers, and a signal generating system, which generates sig-nalappliedtovibrationgenerators.TheperformanceofSFABsiscloselyassociatedwithseveralgoverning parameters, such as the geometry, materials, resonance fre-quency, vibration amplitude, and excitation signal value. Thegeometry plays a crucial role in the SFAB design processbecausethebearingperformancecanberemarkablyenhancedbychoosinganappropriategeometry[121].Inordertoobtainidealbearingperformance,thedesignershouldselecttheappropriate mode shape according to the geometry of thebearinginthedesignprocess.Additionally,itisoftenimportant to consider the effect of the materials on the load-carryingcapacityofthebearing.Studiesshowthatthematerialsaffecttheresonancefrequencyandvibrationamplitude of the SFAB, which results in different squeezefilmeffects[125,133,134].ForSFABs,materialswithalowenergyabsorptioncoefficientandstructuralstiffness willbeabetterchoice.

With regard to the SFABs, the majority of the researchhasfocusedonbearingstructureandvibrationgeneratordesign. The designs of the bearing structure and vibrationgenerator are relatively mature, and the research into bearingstructure and vibration generator design for further improve-mentoftheSFABapplicationinthefieldofmachiningisstillinsufficient since many physical mechanism are not recog-nizedfully.Consequently,thefuturetrendsareasfollows:

(1) Greater load-carrying capacity. In general, the load-carrying capacity of SFABs (only squeeze film effect) islowerthatofconventionalnon-contactbearings.There-fore,theSFABwithgreaterload-carryingcapacityshouldbedeveloped.

(2) Coupledmodelingofsqueezefilmsystems.Duringthe operationofSFABsystems,alargeamountofheatis generated, which leads to thermal deformations. Thesqueeze film levitation model with the thermal-fluid-structure interaction effect should be fully investigatedtheoretically and experimentally, including the influ-enceofheatonfluidandstructuraldeformation.

(3) Activesqueezefilmbearings.Sinceonlyasmallportion oftheliteratureproposedactivesqueezefilmbearings, there is a need for an in-depth investigation into therunningperformanceofthesqueezefilmbearingwithaclosed-loop control system. How to conduct accuratemotion control under different working conditions tothoroughlyunderstandthesqueezefilmlevitationsystemshouldbefurtherinvestigated.

(4) Novelvibrationgenerator.Thevibrationgenerator playsavitalroleinsqueezefilmbearingsystems.In ordertoimprovetherunningperformanceofthebearingandenhancetheefficiencyofenergyutilization,anovelvibration generatorshouldbedeveloped.

(5) Differentlubricantsandexpandingindustrialapplica-tion.Squeezefilmbearingswithotherlubricantsarea criticalissuethatneedstobeinvestigated.Furthermore,the application of squeeze film bearings should not belimitedtoguidewaysandmachinespindles.Otherindustrialapplications,suchasmicroturbines,aircompressors,andturbochargers,needmoreattention.

Conclusions

Non-contact bearings are core components of ultra-precisionmachinetools.ResearchonSFABs,asoneofthenon-contactbearings, has been ongoing for about decades. This reviewpaperconductedasimplecomparisonofthefournon-contactsbearings by evaluating their run time, stability, friction andwear, motion accuracy, energy consumption, etc. The fourkindsofnon-contacttechnologieshavetheirownfeaturesandshouldbeselectedaccordingtotheactualworkingconditions.This paper introduced the fundamental theory for the per-formance prediction of SFABs. Different types of squeezefilmbearings,includingsqueezefilmlinearbearings,thrust bearings,sphericalbearings,andjournalbearings(hybridSFABs), are summarized in this paper, and their principleshavebeenbrieflyintroduced.

Although many investigators have studied the SFABsexperimentallyandnumerically,therearestillgapsindirectlyapplyingSFABstoultra-precisionmachinetools.Inthefuture, development of squeeze film bearings with greaterload-carrying capacity is expected. Thus, a novel vibrationgenerator should be proposed which could be promoted bypotential technologies, including piezoelectric and electro-magnetictechnologies.In-depthinvestigationintothesqueezefilmlevitationmodelwiththethermal-fluid-structureinteraction effect is also required. In addition, active squeezefilm bearings with a closed-loop control system is a furtherdirectionforachievingmoreaccuratemotion,andotherindustrialapplicationsshouldbeexplored.

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