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Influence of capillarity and gravity on confined Faraday wavesS. V. Diwakar,^{1,*} Vibhor Jajoo,² Sakir Amiroudine,² Satoshi Matsumoto,³
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Experiments characterizing the influence of gravity and interfacial tension on Faraday instability in immiscible, confined fluid layers are presented. The variation in interfacial tension was obtained by controlling the temperature of a suitable binary fluid pair while the influence of gravity was analyzed through a series of terrestrial and microgravity (parabolic flight) experiments. These experiments confirm the existence of a crossover frequency, on either side of which gravity plays opposing roles. The current experiments also reveal that the neutral stability curves under Earth's gravity drift toward lower frequencies as the temperature of the liquid pair approaches its upper consolute value, i.e., the temperature of complete miscibility. Such drifts in the low frequency range are shown to occur primarily due to the reduction in density difference between the layers, whereas at very high frequencies they are controlled by the lowering of interfacial tension. In the absence of gravity, the Faraday waves are characterized by larger wave numbers, and, as in terrestrial conditions, the instability thresholds at high frequencies increase with an increase of temperature, i.e., reduction in interfacial tension value. This surprising stabilization originates from the lowering of the critical wavelength that leads to increased viscous dissipation.

DOI: [10.1103/PhysRevFluids.3.073902](https://doi.org/10.1103/PhysRevFluids.3.073902)**I. INTRODUCTION**

The parametric excitation of multilayer fluid systems generates a variety of instabilities based on the fluids' configuration and the direction of vibration. For instance, the case of stably stratified systems leads to two different scenarios depending upon the direction of parametric excitation. The first one, involving vibrations perpendicular to the common interface, results in the phenomenon of Faraday instability [1], whereas the second one pertaining to vibrations parallel to the fluid interface leads to the “frozen wave” instability originating with a Kelvin-Helmholtz mode [2–4]. Even in situations of unstable fluid stratification, that typically result in the well-known Rayleigh-Taylor instability, vertical vibrations of fluid layers have been shown to delay the onset of the instability

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[5,6]. Among such diverse and interesting possibilities, the present work focusses on the classical Faraday instability (perpendicular interfacial excitation) occurring in an immiscible pair of liquids. This instability originates from the resonance between the imposed parametric frequency and the system's natural frequency, which is governed by gravity, capillarity, and the system geometry. The Faraday patterns here vary from well-ordered structures to chaos and encompass both subcritical as well as supercritical modes of instabilities [7–11]. Such remarkable features have given rise to a variety of recent studies ranging from instabilities in self-gravitating spheres [12] and in the presence of patterned/flexible boundaries [13,14] to the development of hydrodynamic quantum analogs [15].

The Faraday instability basically emerges from a competition between the destabilizing inertial forces and the stabilizing effects of interfacial tension and viscosity. These latter properties act to suppress any short wavelength perturbations, thereby stabilizing the fluid layers until a critical excitation amplitude is attained. At the instability threshold, the system's response depends on its lateral boundary conditions. In the first case of infinite/wide lateral extents, the patterns at the onset of the instability manifest with half the forcing frequency, i.e., they are subharmonic. This has been theoretically predicted and experimentally verified [10,16,17]. The patterns exhibited here are of different forms, varying from squares to stripes depending upon the fluid properties and the excitation conditions [6,18–20]. In the second case relating to the practically relevant confined fluid systems, Faraday instability can have access only to a discrete band of modes that need not be subharmonic [11]. Our current interest is to understand the influence of two factors that make up the system's natural frequency, viz., gravity and interfacial tension, on the characteristics of these discrete bands.

Batson *et al.* [21] have theoretically shown that gravity plays a dual role by delaying the instability at low frequencies of excitation and advancing it at high values. In their Fig. 3, it is evident that at low parametric frequency the system is more stable at $1g$ than at zero g , while at high frequency it is the reverse. At first sight, this behavior appears counterintuitive, as one would always expect, regardless of the frequency, enhanced stability at higher gravity level due to the stronger stratification of liquids. However, it can also be argued that any increase in gravity would allow the selection of higher critical wavelength, which, in turn, will reduce the stability brought in by viscous dissipation. Hence, the crossover observed by Batson *et al.* [21] must be a result of an interplay between these two effects. It becomes very important to experimentally characterise them for any potential applications such as vibration-induced atomization [22] and material processing under microgravity.

Interestingly, like gravity, interfacial tension also plays a dual role. This arises from the fact that interfacial tension acts as a restoring force on the deformed interface and any reduction in its value can be expected to result in loss of stability. However, lowering the interfacial tension can also lead to the selection of modes with higher wave number [16], and these are stabilized due to viscosity. Thus, it again becomes essential to understand the competition between these effects for a thorough characterization of the Faraday instability. This task is generally challenging, as it is known from past work [11] that capillarity is insignificant for most experimental fluid systems under Earth's gravity. For interfacial tension to be influential, it is important either to have closely spaced side walls where the wall spacing is of the order of the capillary wavelength or to have high imposed parametric frequency such that the response wavelength is much lower than the capillary wavelength. An alternate means is to completely eliminate the gravity so that the interfacial tension becomes the sole effect that governs the evolution of the instability.

The primary goal of the current study is to experimentally characterize the above dual roles of gravity and interfacial tension. In fact, we intend to specifically analyze the influence of change in these properties on various aspects such as (a) drifts of neutral stability curves, (b) mode discretization, and (c) behavior of critical amplitude at high frequencies. To this end, we have utilized a binary fluid pair whose miscibility and interfacial tension can be easily changed by modifying its temperature. Experiments were performed at different uniform and isothermal conditions below the consolute temperature, i.e., the temperature at which the fluids are miscible, so as to bring out the influence of interfacial tension on the onset of instability. A rectangular cell of suitable dimension was chosen both to make the corresponding interfacial tension effect significant and also to enable a quick change in the fluids' temperature. A series of low-gravity experiments were conducted via flights

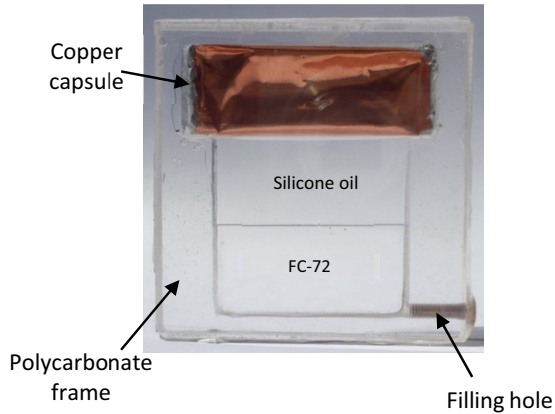


FIG. 1. Experimental test cell with the liquids.

with parabolic trajectories so that a targeted characterization of the interfacial tension effect was possible. In addition, such in-flight experiments helped to address the dual role of gravity and the occurrence of the crossover frequency, on either side of which gravity plays opposing roles. It might be noted that mimicking a low-gravity environment by choosing fluids of equal densities does not help in the case of Faraday instability, as the density difference plays an important role in determining the inertial acceleration obtained by the fluids during oscillations.

Apart from the above scientific interests, a proper understanding of Faraday instability in microgravity conditions is very relevant for all space enabling operations, since all such systems are subjected to periodic gravitational fluctuations via g -jitter. We now describe the details of the experimental setup in the ensuing section, followed by the presentation of results from both terrestrial and microgravity experiments.

II. THE EXPERIMENT

In the current work, an experimental study of Faraday instability in immiscible fluid pairs was performed in the vicinity of the consolute temperature of a specific binary fluid system. A convenient change of the interfacial tension effects was thus enabled by the control of fluid pair temperature. Here, the interfacial tension of the fluid pair tends to zero as the consolute temperature is approached, and beyond this point the fluid pair becomes miscible. It may be noted that a similar elimination of capillarity is also possible either with the use of near critical liquid-vapor systems [23] or, to a lesser extent, with the addition of surfactants [24]. But, these methods to change interfacial tension also bring in significant secondary effects such as a rapidly decaying density difference for the former case and Marangoni convection in the latter. In the current study, the binary fluid pair used is perfluorohexane (FC-72) and octamethyltrisiloxane (1.0 cSt silicone oil), and their consolute temperature (by measurement) for equal volumetric proportions is 42.45 ± 0.05 °C. The densities (ρ) of these oils at 25 °C are 1680 and 816 kg/m³, respectively, while their kinematic viscosities (ν) measure to 0.38×10^{-6} and 1.0×10^{-6} m²/s at 25 °C. Note that the densities of the present fluid layers also change with temperature due to the change in their mutual solubilities. However, the difference in densities does not completely vanish as in the case of near critical fluids [23]. The mixture therefore still provides an excellent opportunity for understanding the influence of interfacial tension.

The experimental system considered in this study used a transparent cell containing FC-72 and 1.0 cSt silicone oil taken at equal volumetric proportions. The temperature of these liquids, which determines the coefficient of interfacial tension, was controlled by circulating water around the cell. The actual configuration of the cell is shown in Fig. 1. The outer dimensions of the cell were 55 mm

(width) \times 55 mm (height) \times 7 mm (depth). The cell consisted of a polycarbonate frame which was sandwiched between two 55 mm \times 55 mm \times 1 mm (thickness) sapphire glasses at the front and the back. The use of sapphire material reduced the resistance for heat transfer between the liquids and the circulating water. A sealed copper capsule with trapped air was placed in contact with the silicone oil in the cell interior. This capsule easily contracted/expanded to compensate for the thermal expansion/contraction of the liquids. The copper capsule was snugly fitted into a matching slot with epoxy glue and, hence, there was no independent motion of the capsule within the cell. The dimensions of the inner region encompassed by the liquids (excluding the volume occupied by the copper capsule) were 35 mm (width) \times 29.3 mm (height) \times 5 mm (depth). The current cell depth of 5 mm is an optimum value, considering the necessity for attaining faster thermal equilibrium of liquids with the circulating water, particularly in the parabolic flight experiments. Though a cell even narrower than 5 mm would have better suited heating/cooling of liquids and for making the interfacial tension effects dominant, it was avoided so that the critical amplitude remained within the measurement range of the current linear oscillator. Note that the critical amplitude increased drastically with the decrease in cell depth.

In the present configuration, the binary liquids were filled through the side hole by suitably tilting the cell to completely evacuate the air. Once the cell was fully filled with liquids, the hole was sealed using a threaded screw wrapped with polytetrafluoroethylene (PTFE). The circulating water for the control of the liquids' temperature was actuated by a pump. The desired temperature in the circuit (with a stability of ± 0.01 °C) was achieved using a proportional integral-derivative (PID) controlled immersion heater. The heater controller received temperature feedback from a Pt-100 probe suitably located in the circuit. Aside from the heating, the water circuit was also equipped with a feedback controlled Peltier element for cooling the liquids when required.

The cell along with the enclosure for the circulating water was mounted on a vertically oscillating platform which was actuated by a linear drive with servo control of speed. The motion of the drive was computer controlled and allowed a maximum acceleration of approximately 3g with frequencies up to 15 Hz. The amplitudes (A) and frequencies (f) were observed to be within 2% and 0.1% of their respective set values. The onset of the instability was recorded using a high speed camera (Photron SA3 60 K M2). The illumination for the imaging process was obtained through an LED light placed behind the cell, on the moving platform. Generally, the motion of the interface was captured at 250 images per second with an exposure time of 5 μ s. The recorded images were digitized and calibrated into length scales from which the size of the instability (wavelengths) was measured. The error in wavelength measurements was estimated to be about $\pm 5\%$ based on the processed images. In order to maintain the saturation of fluids with respect to solubility, they were shaken vigorously ($A = 30$ mm and $f = 3$ Hz) for 30 s followed by a wait time of 30 s before each experimental trial. This was necessary to obtain repeatable results from the experiments.

III. RESULTS

Two sets of experimental results are currently reported, viz., terrestrial experiments and microgravity experiments. For each set, the temperature was varied through a definite range in which both the density difference and the interfacial tension were changing. A known oscillation frequency was imposed and the lowest excitation amplitude for which a discernible interfacial wave occurred was measured. The aim of the terrestrial experiments was to primarily understand the behavior of the resulting neutral curves when the temperature of the binary mixture approaches the upper consolute value. On the other hand, the purpose of the microgravity experiments was threefold: first, to show via a comparison with terrestrial experiments, the existence of the crossover frequency that separates the regimes where the gravity plays opposing roles; second, to observe the mode discretization behavior at low gravity; third, to see the effect of lowering the interfacial tension in the absence of gravity.

At this stage, two important factors have to be noted with regard to the present binary fluid system and the experimental configuration. First, the coefficient of interfacial tension for the FC-72/silicone oil pair is very low. The value at 25 °C is 0.77 mN/m and it further diminishes as the

fluids' temperature progressively approaches the consolutal state, which is the region of present interest. Measuring such low values of interfacial tension coefficient is very difficult. In view of this fact and the unavailability of such data in the open literature, the results have been presented here in unscaled quantities as opposed to the convention of nondimensional representation. Fortunately, this does not impede the understanding of physics that emanate from the current work. The second factor concerns the "meniscus waves" that originate from the dynamic variation of fluid interface's contact angle with the side walls [10]. For the present cell of narrow depth, the measured instability thresholds included some contribution of the damping that arises from the meniscus waves. This was despite the favorable wetting attributes of silicone oil that made it form a thin film on the surface, thus allowing for a semislippery motion of the contact line. If the side walls were spaced well apart (at distance several times the capillary length), the damping effect from the sliding contact line would have become insignificant and an almost perfect agreement between theory and experiments could be realized, as demonstrated by Batson *et al.* [11]. However, for the present narrow system such elimination of damping is not possible. Unfortunately, there is no simple theoretical model that can represent the underlying physics of meniscus waves. The existing theoretical approaches like the one proposed by Kumar and Tuckerman [17] do not have an explicit mechanism that mimics the side wall damping, even though they efficiently model the internal viscous damping. Hence, for this reason and for the unavailability of surface tension data, we do not provide an explicit comparison with any theoretical dispersion curves. Instead, we make a qualitative connection to the simplified theory of Benjamin and Ursell [16] in all the cases. In fact, it will be evident that this simple model satisfactorily explains many of the fundamental modifications in Faraday waves arising due to the change of interfacial tension and gravity. To this end, we commence our discussions with the results obtained from the terrestrial experiments. Note that for all experiments under Earth's gravity, the critical amplitudes have been measured within an error of ± 0.02 mm, whereas this was not possible in microgravity flights as the corresponding zero g time window was very short. Thus, the error in critical amplitudes for microgravity experiments were obtained within a margin of ± 0.25 mm.

A. Terrestrial experiments

Figure 2 shows the critical amplitude, A_{cr} , obtained for frequencies ranging between 3 and 8 Hz at four different temperatures, viz., 38°C , 40°C , 41.5°C , and 42°C , under terrestrial conditions. In this narrow temperature range, the interfacial tension coefficient drastically diminishes as the temperature of the fluids approaches the consolute value ($42.45 \pm 0.05^\circ\text{C}$). Figure 2(a) shows the graph of variation in A_{cr} with frequency at $T = 38^\circ\text{C}$. It can be observed that the current confined system at low frequencies is characterized by both harmonic and subharmonic modes occurring over discrete bands of frequencies. This is in contrast to a continuum of subharmonic modes that are seen in large-aspect systems [17]. The various modes are labeled as A, B, C, etc., and are depicted in Fig. 3. Here, mode B alone is harmonic and it consists of two and a half waves. The rest of the modes are subharmonic and feature as multiples of the half wave, i.e., A consists of a half wave, C consists of a full wave, D consists of one and a half waves, and so forth. Within each of the discrete bands, the critical amplitude attains a minimum at the natural frequency of the mode. This behavior is analogous to that of damped, driven linear oscillators whose response amplitude primarily depends on the forcing frequency and attains a maximum when it is equal to the system's natural frequency. For the present case of Faraday instability, a similar effect produces a minimum of criticality at the natural frequency of each mode. Generally, any perturbation/undulation of the fluid interface will produce an ingress of heavier fluid into the lighter fluid along the crests, and vice versa along the troughs. The acceleration-induced inertial force acting on these fluid masses further amplifies the undulation, i.e., the instability, while the effects such as gravity, interfacial tension, and the viscous diffusion act as restoration forces that bring back the interface to its initial flat condition.

The impact of changing fluid temperature on the onset characteristics is depicted in Figs. 2(b), 2(c), and 2(d). In the present case, the increase in temperature leads to decreases in both the density difference (note that the density of each layer changes on account of the solubility) and the interfacial

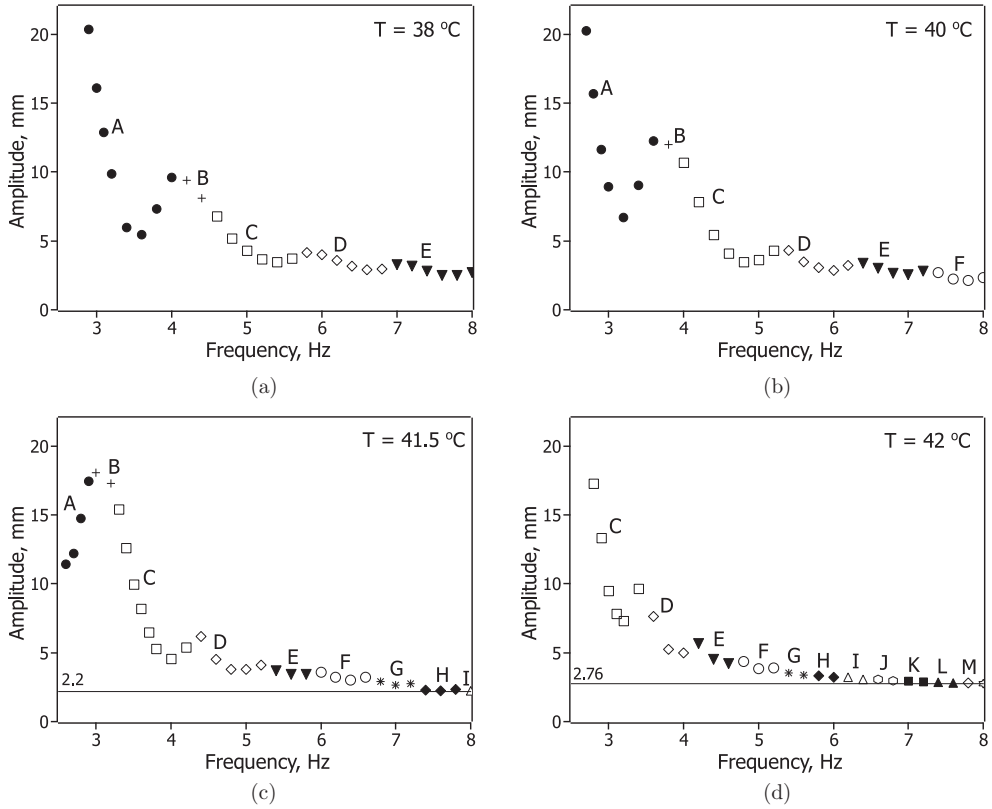


FIG. 2. Critical amplitude required for the onset of Faraday instability in confined, immiscible FC-72/silicone oil system at different temperatures under terrestrial conditions: (a) 38 °C, (b) 40 °C, (c) 41.5 °C, (d) 42 °C. The labels A, B, C, etc., represent the various modes and are described in the text.

tension. To get a qualitative feel for their respective roles, it would be helpful to consider the simple theoretical model put forth by Benjamin and Ursell [16], who produced the following Mathieu equation in the case of Faraday instability with inviscid fluids:

$$\ddot{\zeta} + \omega_0^2[1 - \hat{a} \cos(\omega t)]\zeta = 0. \quad (1)$$

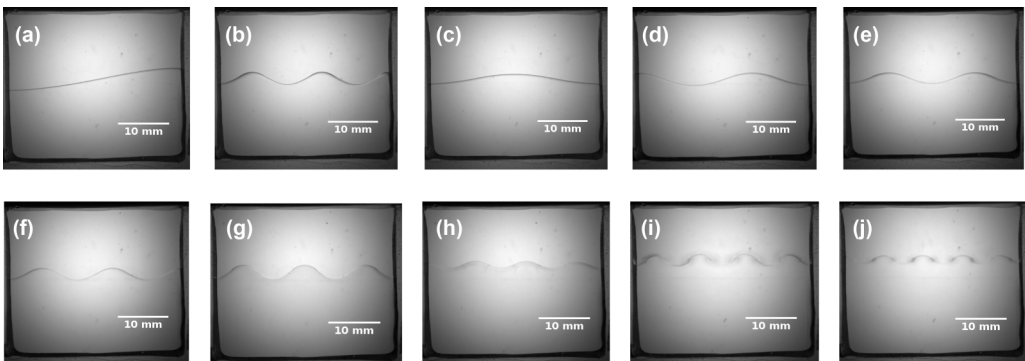


FIG. 3. Interfacial modes of excitation at onset, depicted in Fig. 2. While B alone is harmonic, all other modes are subharmonic.

Here, ζ is the interfacial deformation and ω is the imposed frequency ($=2\pi f$). The natural frequency, ω_0^2 , is obtained from the dispersion relation for gravity-capillary waves and is given as

$$\omega_0^2 = \frac{(\rho_1 - \rho_2)gk + \sigma k^3}{\rho_1 + \rho_2}, \quad (2)$$

and the term \hat{a} is given by

$$\hat{a} = \frac{(\rho_1 - \rho_2)A\omega^2 k}{(\rho_1 + \rho_2)\omega_0^2}, \quad (3)$$

where A , k , g , and σ are the values of excitation amplitude, wave number, gravitational acceleration, and coefficient of interfacial tension, while ρ_1 and ρ_2 are the densities of bottom and top fluids, respectively.

It is evident from Eq. (2), that the natural frequency of the Faraday system, at a particular wave number, is influenced by both the interfacial tension as well as the density difference. Thus, if either of them were to be modified then the system must respond by changing either its natural frequency or by changing the response wave number if the natural frequency were to be maintained constant. In fact, these are the exact features one can observe in Fig. 2. First, there is an obvious drift of modes toward lower frequencies of excitation as the temperature is increased. In other words, the natural frequency of each mode becomes smaller and the frequency band for each mode shrinks as both the density difference and the interfacial tension decrease. Second, the drift of modes leads to the reduction of critical wavelength for certain forcing frequencies as the temperature is increased. For example, the interfacial mode at onset for a frequency of 6 Hz has changed from mode *D* to mode *F* and then to mode *H* as the temperature progressed from 40 °C to 41.5 °C and then to 42 °C.

The actual effect that contributes to the above behavior depends on the forcing frequency as both interfacial tension and density difference have their characteristic zones of influence. Note that the interfacial tension term becomes comparable with the gravitational term only when the wave number is of the order $\sqrt{(\rho_1 - \rho_2)g/\sigma}$. Thus, at lower parametric frequencies where the response wave number of the Faraday instability is smaller, the gravitational term, $(\rho_1 - \rho_2)gk$, mainly determines the instability characteristics as it is of $O(k)$. At higher frequencies where the response wave number is larger, it is the interfacial tension term that plays the dominant role as it is of $O(k^3)$. In other words, the interfacial tension would play a significant role only when the manifested wavelength of the Faraday waves is equal to or less than the capillary length scale, l_c , which is defined as $l_c = \sqrt{\sigma/(\rho_1 - \rho_2)g}$. In contrast, any response wavelength larger than l_c corresponds to the dominance of density difference. For the current fluid combination, i.e., FC-72/1.0 cSt silicone oil with $\rho_1 = 1680 \text{ kg/m}^3$, $\rho_2 = 816 \text{ kg/m}^3$, and $\sigma = 0.77 \text{ mN/m}$ (all at 25 °C), the capillary length scale is approximately 0.3 mm. Since, the critical wavelengths at the lower frequencies are presently larger than this value (see Fig. 3), any change in the interfacial tension cannot have a notable impact on the instability pattern. Therefore, the only significant contribution to the natural frequency comes from the gravitational term, $(\rho_1 - \rho_2)gk$.

It may be recalled that for resonant interfacial oscillations there ought to be a match between the imposed frequency and the natural frequency of the system. Hence, for a given imposed frequency in the low frequency range, the gravitational term has to be maintained constant irrespective of the temperature of the fluids. This implies that any change in the density difference should involve a corresponding increase in the critical wave number, and this is what is observed in the experiments (Fig. 2). Only at high frequencies where the response wave numbers are higher does the reduction in interfacial tension influence the instability. The decrease in the interfacial tension is expected to be significant near the consolutal temperature, and, as can be seen from Eq. (2), the response wave number must become very large to maintain the system's natural frequency. The mode discretization therefore becomes difficult to discern and one can even expect a continuous change of wavelength with the frequency, for which the evidence starts to appear at 42 °C [Fig. 2(d)].

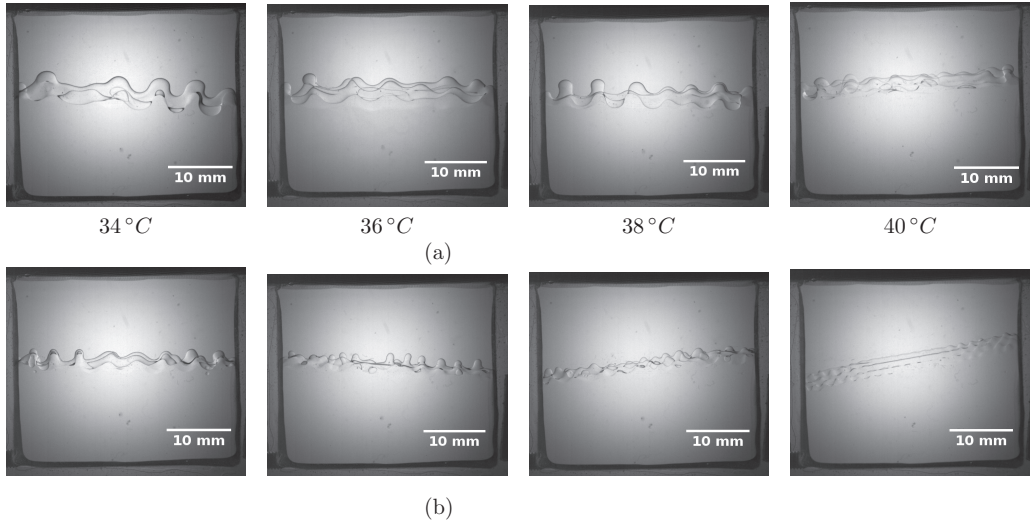


FIG. 4. Interfacial modes of excitation in microgravity conditions for different temperatures and forcing frequencies. (a) 7 Hz, (b) 11 Hz.

As far as the critical threshold is concerned, it is difficult to give its exact trend of variation at lower frequencies, as the drifting of modes can correspondingly make a frequency either more stable or more unstable with respect to the temperature. One may see this effect for the frequency of 4.4 Hz at different temperatures in Fig. 2. However, a clearer pattern is apparent at higher frequencies where the curves tend toward a constant value of critical amplitude, independent of the frequency/mode. Interestingly, this amplitude shows an increase with the increase of temperature; see Figs. 2(c) and 2(d). In other words, the system actually becomes more stable with the reduction of interfacial tension. This behavior might appear counter-intuitive, as one would normally expect a reduced restoration force in such situations. However, the selection of higher wave number that leads to larger viscous dissipation must play a stabilizing role. In other words, the instability brought in through the reduction of interfacial tension effects is overwhelmed by the viscous stabilization, particularly when the operating conditions are closer to the consolute point. Another notable outcome of temperature change in the vicinity of the consolute value is the reduction in meniscus thickness, which would minimize the damping effects brought in by the meniscus waves.

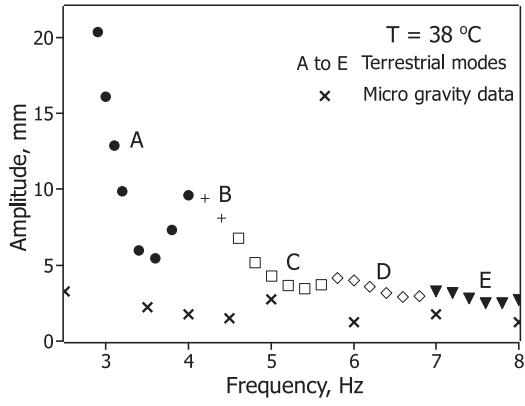
In summary, we can clearly see from the terrestrial experiments that all the modes shift toward a lower frequency as the fluids temperature is increased. In fact, this mode shift is what that might be expected upon inspection of the natural frequency given in Eq. (2) by the Benjamin and Ursell theory [16]. However, both the density difference as well as the interfacial tension decrease with an increase in temperature and it is impossible to experimentally isolate the change happening due to one effect from the other. It is evident from the theory that the density difference plays a dominant role at low frequency and interfacial tension at high frequency. Fortunately, we can eliminate the importance of density difference by performing the experiments in microgravity and also obtain evidence of the crossover frequency on either side of which gravity plays an opposing role. To this end, we now discuss the results obtained from the microgravity experiments.

B. Microgravity experiments

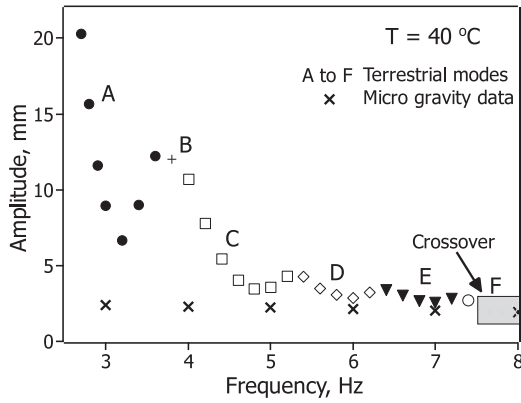
Microgravity levels of the order of $10^{-2}g$ may be obtained by conducting the experiments onboard an aircraft undergoing a parabolic path. Figure 4 shows the post-onset interfacial patterns obtained on flight for different temperatures and two forcing frequencies, 7 and 11 Hz. In contrast with Fig. 3 where the modes are apparently two-dimensional, some perpendicular features of interfacial deformation

are visible owing to the random fluctuations of gravity imposed by the aircraft. Notwithstanding these inevitable fluctuations, a drastic reduction in the wavelength is observed as compared to terrestrial conditions. A clear example of this can be seen by comparing panel E of Fig. 3, i.e., the mode seen at terrestrial conditions for 7 Hz and 38 °C, to the corresponding micro-gravity behavior shown in the third panel of Fig. 4(a). The reason for this reduction may be seen by once again referring to the term $(\rho_1 - \rho_2)gk$ in Eq. (2), which indicates that the reduction in gravity must accompany an increase in critical wave number, k , if resonance with the parametric excitation is to be achieved. An appropriate physical analog can be made with the help of an oscillating pendulum whose natural frequency is proportional to $\sqrt{g/l}$, where l is the distance between the pivot and the bob. If the pivot is subjected to parametric excitation, a resonance is established when the natural and the imposed frequencies are suitably tuned [25]. In this situation, if gravity acting on the system is reduced, then l ought to decrease so as to keep the natural frequency the same as before and maintain resonant conditions. A similar effect is observed in the case of the fluid Faraday system where the wavelength of the interfacial deformation reduces so as to compensate the reduction in gravity. With the elimination of gravity, Fig. 4 shows the sole effect of reduction in interfacial tension. Temperatures up to 40 °C have been depicted and it is evident that the wavelength is reduced as the temperature increases. Near the consolutal temperature (not shown here), it was very difficult to decipher the difference between the minute interfacial deformations from the random fluctuations due to aircraft jitter.

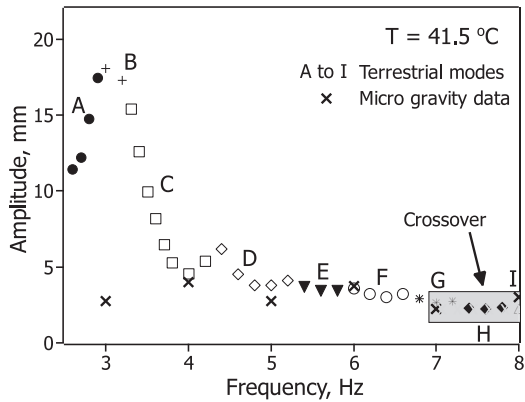
Figure 5 shows the range of threshold amplitude obtained for three different temperatures, viz., $T = 38$ °C, $T = 40$ °C, and $T = 41.5$ °C under microgravity conditions along with corresponding terrestrial data. Note that the 20 microgravity threshold values shown in the Fig. 5 were obtained from five different parabolic flight campaigns involving 465 parabolas. Lots of checks and balances were put in place to distinguish between the true Faraday patterns and the interfacial disturbances originating from random aircraft fluctuations. The foremost of these checks involved verifying the flight acceleration data in all the three axes. Correspondingly, parabolas with maximum acceleration amplitude less than ± 0.02 m²/s were only chosen for evaluating the threshold. In the next stage, the captured image sequences were processed in the IMAGEJ software to check if the frequency of the interfacial patterns matched with the actual imposed frequency. Finally, all the thresholds were repeatedly verified to check if the instability/stability occurs within 0.25 mm above/below the stated threshold. Despite all these strenuous efforts, the micro-gravity thresholds are mentioned here to have an error of ± 0.25 mm for two reasons. First, a more precise measurement of the threshold was not possible due to the short low- g time window available in parabolic flights. The time required to observe a tangible interfacial wave actually increases as the threshold is approached. So, within the time frame of 15–20 s provided by the parabolic flights, only an estimated range for the threshold could be obtained. Second, this large error bar would conservatively include all the uncertainty one may encounter from the random aircraft fluctuations. In Fig. 5, the error bars are within the size of the crosses that have been used to represent the microgravity data and the results clearly show that the critical amplitude is reduced drastically due to low g in the low frequency range for all the temperatures. This happens despite the fact that the wavelength also has undergone a drastic reduction which ordinarily makes the system more stable owing to the increased viscous dissipation. As explained earlier and shown by Fig. 3 of Batson *et al.* [21], there is a crossover frequency below which the system was found to be destabilized in the absence of gravity. The present experiments clearly depict the existence of this cross-frequency and its drift to lower frequencies as the coefficient of interfacial tension is decreased. Figure 5(a) shows that for $T = 38$ °C the crossover frequency is above the range of frequencies considered in this work. However, for $T = 40$ °C the crossover frequency seems to occur around 8 Hz, and for $T = 41.5$ °C the microgravity data intersect the terrestrial data well below 8 Hz. The approximate location of the crossover frequency has been marked in Figs. 5(b) and 5(c) as a shaded region. Figure 6 shows the comparison of microgravity data for three different temperatures. It is most important to note here that the critical amplitude of excitation has typically increased with the increase in temperature. In the absence of any influence from the gravitational term, this surprising effect clearly shows that stability has increased with the decrease of interfacial tension. Once again the decrease in the wavelength of the Faraday waves that



(a)



(b)



(c)

FIG. 5. Threshold range measured in microgravity conditions in comparison with terrestrial experiments at temperatures (a) $T = 38\text{ }^{\circ}\text{C}$, (b) $T = 40\text{ }^{\circ}\text{C}$, (c) $T = 41.5\text{ }^{\circ}\text{C}$.

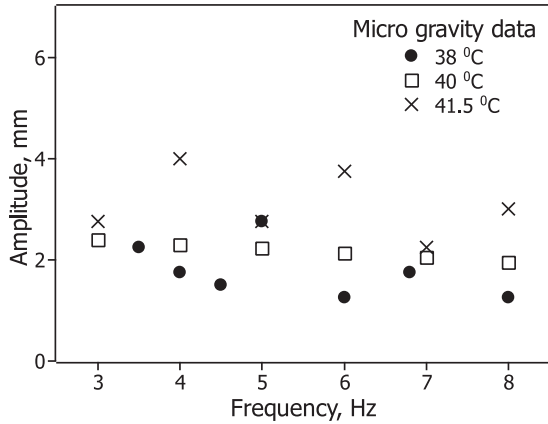


FIG. 6. Threshold range measured in microgravity conditions for different temperatures. Observe that the critical amplitude typically increases with an increase in temperature.

led to the increased viscous dissipation explains the observed stabilization of the layer. This also agrees with earlier results observed in the terrestrial experiments. The last observation is the loss of clear discretization of the instability under microgravity conditions and, correspondingly, the earlier seen patterns A, B, C, D, etc. in the terrestrial experiments are not apparent now. This aspect of the experiments also qualitatively agrees with the theoretical predictions.

IV. CONCLUSIONS

In the present set of experiments, involving FC-72 and 1.0 cSt silicone oil, interfacial tension and gravity have been independently controlled to obtain a deeper understanding of the Faraday instability. Correspondingly, interesting information is evident from the current terrestrial and zero-gravity experiments:

(1) Of foremost interest is the behavior of neutral stability curves under terrestrial conditions wherein they shift toward lower frequencies as the temperature of the binary fluid pair is increased. Since both density difference and interfacial tension decrease with the increase of temperature, it is difficult to associate the drifting behavior to either of these effects merely by observing the experimental results. However, in qualitative agreement with the inviscid theory of Benjamin and Ursell [16], it is shown that density difference plays a dominant role in determining the shift at low forcing frequencies where the response wave number is very small. Only when the parametric frequency is higher does the wavelength of the Faraday instability become comparable to the capillary length scale and does the interfacial tension shows its influence.

(2) Another important feature of the present work is the unequivocal confirmation of the existence of a crossover frequency, below and above which gravity plays opposing roles. This was evident from the parabolic flight experimentation, which also provided a unique opportunity to understand the sole influence of interfacial tension effects. In fact, the reduction of interfacial tension coefficient in low- g conditions led to the lowering of this crossover frequency.

(3) Interestingly, in both experimental sets, the reduction of interfacial tension with temperature increases the stability of the system. This counterintuitive effect occurs on account of increased viscous dissipation that results from increased choppiness of waves at lower surface tension. This shows that the secondary effect of change in the critical wavelength, and thus the increase in viscous damping, overwhelms the primary effect of change in interfacial tension.

(4) A clear loss of mode discretization is also evident in the absence of gravity. It may be noted that that such aspects of the present results are in qualitative agreement with the theory of Benjamin and Ursell [16].

(5) Finally, the understanding of Faraday instability in microgravity emanating from the current work has potential applications in thermal management and bubble removal for various space-enabling operations.

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- [1] M. Faraday, On a peculiar class of acoustical figures; and on certain forms assumed by groups of particles upon vibrating elastic surfaces, *Philos. Trans. R. Soc. London* **121**, 299 (1831).
- [2] M. V. Khenner, D. V. Lyubimov, T. S. Belozeroва, and B. Roux, Stability of plane-parallel vibrational flow in a two-layer system, *Eur. J. Mech. B, Fluids* **18**, 1085 (1999).
- [3] E. Talib, S. V. Jalikop, and A. Juel, The influence of viscosity on the frozen wave instability: Theory and experiment, *J. Fluid Mech.* **584**, 45 (2007).
- [4] Y. A. Gaponenko, M. Torregrosa, V. Yasnou, A. Mialdun, and V. Shevtsova, Dynamics of the interface between miscible liquids subjected to horizontal vibration, *J. Fluid Mech.* **784**, 342 (2015).
- [5] G. H. Wolf, Dynamic Stabilization of the Interchange Instability of a Liquid-Gas Interface, *Phys. Rev. Lett.* **24**, 444 (1970).
- [6] M. Bestehorn and A. Pototsky, Faraday instability and nonlinear pattern formation of a two-layer system: A reduced model, *Phys. Rev. Fluids* **1**, 063905 (2016).
- [7] R. Keolian, L. A. Turkevich, S. J. Putterman, I. Rudnick, and J. A. Rudnick, Subharmonic Sequences in the Faraday Experiment: Departures from Period Doubling, *Phys. Rev. Lett.* **47**, 1133 (1981).
- [8] J. P. Gollub and C. W. Meyer, Symmetry-breaking instabilities on a fluid surface, *Physica D* **6**, 337 (1983).
- [9] S. Douady and S. Fauve, Pattern selection in Faraday instability, *Europhys. Lett.* **6**, 221 (1988).
- [10] S. Douady, Experimental study of the Faraday instability, *J. Fluid Mech.* **221**, 383 (1990).
- [11] W. Batson, F. Zoueshtiagh, and R. Narayanan, The Faraday threshold in small cylinders and the sidewall non-ideality, *J. Fluid Mech.* **729**, 496 (2013).
- [12] A.-h. E. Adou and L. S. Tuckerman, Faraday instability on a sphere: Floquet analysis, *J. Fluid Mech.* **805**, 591 (2016).
- [13] J. Feng, I. Jacobi, and H. A. Stone, Experimental investigation of the Faraday instability on a patterned surface, *Exp. Fluids* **57**, 86 (2016).
- [14] G. Pucci, E. Fort, M. Ben Amar, and Y. Couder, Mutual Adaptation of a Faraday Instability Pattern with its Flexible Boundaries in Floating Fluid Drops, *Phys. Rev. Lett.* **106**, 024503 (2011).
- [15] J. W. M. Bush, Pilot-wave hydrodynamics, *Annu. Rev. Fluid Mech.* **47**, 269 (2015).
- [16] T. B. Benjamin and F. Ursell, The stability of the plane free surface of a liquid in vertical periodic motion, *Proc. R. Soc. London, Ser. A* **225**, 505 (1954).
- [17] K. Kumar and L. S. Tuckerman, Parametric instability of the interface between two fluids, *J. Fluid Mech.* **279**, 49 (1994).
- [18] B. Christiansen, P. Alstrøm, and M. T. Levinsen, Ordered Capillary-Wave States: Quasicrystals, Hexagons, and Radial Waves, *Phys. Rev. Lett.* **68**, 2157 (1992).
- [19] A. Kudrolli and J. P. Gollub, Patterns and spatiotemporal chaos in parametrically forced surface waves: A systematic survey at large aspect ratio, *Physica D* **97**, 133 (1996).
- [20] J. Rajchenbach and D. Clamond, Faraday waves: Their dispersion relation, nature of bifurcation and wavenumber selection revisited, *J. Fluid Mech.* **777**, R2 (2015).

- [21] W. Batson, F. Zoueshtiagh, and R. Narayanan, Dual role of gravity on the Faraday threshold for immiscible viscous layers, [Phys. Rev. E](#) **88**, 063002 (2013).
- [22] A. J. James, B. Vukasinovic, M. K. Smith, and A. Glezer, Vibration-induced drop atomization and bursting, [J. Fluid Mech.](#) **476**, 1 (2003).
- [23] S. Fauve, K. Kumar, C. Laroche, D. Beysens, and Y. Garrabos, Parametric Instability of a Liquid-Vapor Interface Close to the Critical Point, [Phys. Rev. Lett.](#) **68**, 3160 (1992).
- [24] S. Kumar and O. K. Matar, On the Faraday instability in a surfactant-covered liquid, [Phys. Fluids](#) **16**, 39 (2004).
- [25] A. H. Nayfeh and D. T. Mook, *Nonlinear Oscillations* (John Wiley & Sons, New York, 1995).