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REVIEW, STUDY AND EVALUATION OF POSSIBLE FLIGHT
EXPERIMENTS RELATING TO CLOUD PHYSICS EXPERIMENTS IN SPACE

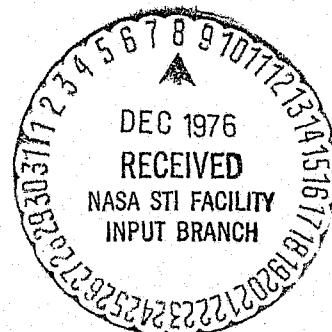
by

R. J. Hung and S. T. Wu

Final Technical Report

This research work was supported by
the National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Contract No. NAS8-30247

The University of Alabama in Huntsville
P. O. Box 1247
Huntsville, Alabama 35807



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The manuscript was typed by Ms. Carol Holladay. Her patient and skillful typing was essential in bringing this report to its present form.

SUMMARY

Recently, studies of the dynamics of oscillations, rotations, collisions and coalescence of water droplets have triggered the imagination of researchers in various fields of physical sciences, such as meteorology, nuclear physics, astrophysics, fluid mechanics, mechanical engineering and chemical engineering. For experimental observation of the dynamics of liquids in the terrestrial laboratory, artificial supports are required to eliminate the gravitational force and to provide a longer observation time. These artificial supports tend to mask other types of minute forces and disturb the original effects which might confuse the experimental observations. Experiments performed in an arbitrary spacecraft with its low gravity environment offer a technique to study fluids, observe their modes of oscillations, rotations, collisions and coalescence without the side effects of artificial suspension techniques.

To take advantage of the zero-gravity experiments in fluid mechanics of Skylab III and IV, we granted subcontracts to four scientists to analyze the Skylab experiments. The inhouse analysis of the Skylab experiments in dynamics of oscillations, rotations, collisions and coalescence of water droplets under low gravity-environment resulted in four publications. A group of scientists from the cloud physics scientific community were also invited to serve as consultants to provide advice and guidance for the definition of experiments and scientific input to the Atmospheric Cloud Physics Laboratory at the Shuttle-Spacelab mission.

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I. INTRODUCTION

The general objectives of the Zero-Gravity Atmospheric Cloud Physics Laboratory Program are to improve the level of knowledge in atmospheric cloud physics research by placing at the disposal of the terrestrial-bound atmospheric cloud physicist a laboratory that can be operated in the environment of zero-gravity or near zero-gravity. This unique laboratory will allow studies to be performed without mechanical, aerodynamic, electrical, or other techniques to support the object under study.

The cloud physics research under zero or low gravity conditions offers an opportunity to answer many problems that can not be solved in earth-based laboratories. By taking advantage of zero gravity to define many of the processes in clouds that are not yet fully understood, man could influence weather by changing, for example, drop distributions and nuclei concentrations or by adding pollutant compositions.

Recently, the study of drops and bubbles has drawn great attention among the researchers in various fields. Researchers who are interested in drops and bubbles can be classified as follows: (1) nuclear physicists use liquid drops and bubbles as models to investigate the phenomena of nuclear fusion and fission; (2) astrophysicists use rotations and oscillations of liquid drops as models to study binary stars and rotating stars; (3) meteorologists use collision and coalescence of liquid drops as models to study growth and breakup of raindrops and formation of clouds; (4) mechanical and chemical engineers use the dynamics of liquid drops and bubbles to investigate the flow instability problem especially

in the system of two-phase flow; and (5) fluid dynamists use liquid drops and bubbles as models to study potential flow and viscous flow problems in fundamental fluid dynamics.

The impact of zero-gravity experiments on future research is quite significant. Experiments performed in an orbiting spacecraft under zero-gravity conditions allow observations of phenomena which normally can not be done in a terrestrial laboratory. An example of such an observation is that of the colliding of two water droplets which are not supported by any of the following levitation apparatuses, such as: (1) aerodynamic force by using vertical wind tunnel; (2) electrostatic force by using applied electrostatic potential; (3) acoustical pressure generated by high frequency acoustic waves; or (4) optical pressure generated by high tension laser beams. Any of the above techniques tends to dampen the oscillations of the water droplets and to mask other types of phenomena. Furthermore, the maximum size of the water droplet under one-G condition is on the order of a thousand microns while the size of the water droplet is on the order of centimeters or more under zero-G conditions.

To take advantage of zero-gravity experiments in fluid mechanics; at Skylab III and IV, the following activities have been performed under the support of the present contract.

- (1) A group of scientists from the cloud physics scientific community have been invited to serve as consultants to provide the advice and the guidance of the definition of experiments and scientific input to the Atmospheric Cloud Physics Laboratory at the Shuttle-Spacelab mission.

- (2) Several subcontracts have been granted under the present contract to scientists in the cloud physics scientific community to analyze the Skylab experiments relevant to drop collisions, coalescence, rotations, and droplet oscillation.
- (3) Inhouse analysis of the Skylab experiments. Four papers based on the analysis from Skylab III and IV experiments are included in this report.

II. CONSULTANTS FROM THE CLOUD PHYSICS SCIENTIFIC COMMUNITY

A group of scientists from the cloud physics scientific community were asked to serve as consultants for the present contract. The purpose of the service is to provide the advice and the guidance of the definition of experiments and scientific input to the cloud physics laboratory project which are significant to assume successful experiments on the future Shuttle-Spacelab Cloud Physics Laboratory under low gravity environment. These consultants from the scientific community have proven to be very critical to the development of the zero-gravity cloud physics laboratory. The following scientists came to Huntsville, Alabama, or other locations as requested by the present contract, as consultants for this contract:

- (1) Dr. Charles A. Anderson
University of Wisconsin, Madison, Wisconsin.
- (2) Dr. Larry Berkbigler
University of Missouri - Rolla, Rolla, Missouri.
- (3) Dr. D. C. Blanchard
State University of New York, Albany, New York.
- (4) Dr. John C. Carstens
University of Missouri - Rolla, Rolla, Missouri.
- (5) Dr. Kenneth Dunipace
University of Missouri - Rolla, Rolla, Missouri.
- (6) Dr. Harry Edwards
Colorado State University, Fort Collins, Colorado.
- (7) Dr. Donald Hagen
University of Missouri - Rolla, Rolla, Missouri.

- (8) Dr. Peter Hobbs
University of Washington, Seattle, Washington.
- (9) Dr. Thomas E. Hoffer
University of Nevada System-Reno, Reno, Nevada.
- (10) Dr. Charles Hosler
Pennsylvania State University, University Park, Pennsylvania.
- (11) Dr. James Hudson
University of Nevada System-Reno, Reno, Nevada.
- (12) Dr. K. O. L. F. Jayaweera
University of Alaska, Fairbanks, Alaska.
- (13) Dr. James L. Kassner
University of Missouri-Rolla, Rolla, Missouri.
- (14) Mr. Warren Kocmond
Calspan Corporation, Buffalo, New York.
- (15) Dr. Garland Lala
State University of New York, Albany, New York.
- (16) Dr. C. L. Lin
University of Missouri - Rolla, Rolla, Missouri.
- (17) Dr. Henry Loos
Laguna Research Lab., Laguna Beach, California.
- (18) Dr. C. K. Liu
University of Alabama in Tuscaloosa, University, Alabama.
- (19) Dr. Jorge A. Pena
Pennsylvania State University, University Park, Pennsylvania.
- (20) Dr. Fred Rogers
University of Nevada System-Reno, Reno, Nevada.

- (21) Mr. Bob Ruskin
Naval Research Laboratory, Washington, D. C.
- (22) Dr. Bob Sax
Experimental Meteorology Lab., Coral Gables, Florida.
- (23) Dr. J. D. Spengler
Harvard University, Cambridge, Massachusetts.
- (24) Dr. Pat Squires
University of Nevada System—Reno, Reno, Nevada.
- (25) Dr. Gabor Vali
University of Wyoming, Laramie, Wyoming.
- (26) Dr. James W. Telford
University of Nevada System—Reno, Reno, Nevada.
- (27) Dr. Helmut Weickmann
NOAA, Boulder, Colorado.
- (28) Dr. Dan White
University of Missouri-Rolla, Missouri.

The above scientists have served one or more times as a consultant.

III. SUBCONTRACTS FOR THE ANALYSIS OF SKYLAB EXPERIMENTS

The cloud physics research under zero- or low-gravity conditions offers an opportunity to answer many problems that can not otherwise be solved on earth-bounded laboratories. By taking advantage of zero gravity to define many of the processes in clouds that are not yet fully understood, man can influence weather by changing, for example, drop distributions and nuclei concentrations, or by adding pollutant compositions.

Recently, during the Skylab III and IV missions, astronauts have performed a series of zero-gravity demonstrations and also the collisions and coalescences of water droplets. The natural oscillations and dissipations of water droplets are of special interest, since it may provide a mechanism for droplet breakup in clouds. In the meanwhile, studies of the collision and coalescence of water droplets will offer valuable information about raindrops growth and breakup processes.

In order to utilize the results from the Skylab experiments to some greater extent, several subcontracts have been granted to experts in the field of cloud physics to analyze the Skylab experiments relevant to drop collisions, coalescence and droplet oscillations.

The publications accomplished from the study of the Skylab experiments based on support from the present contract are as follows:

- (1) "Interactions Between Drops Observed During Skylab Experiments January 1974," by D. A. Lawler and C. E. Anderson (Department of Meteorology, University of Wisconsin, Madison, Wisconsin 53706).

The conclusions made by Lawler and Anderson are as follows:

The results of the Skylab demonstrations support the existing literature in predicting the occurrence of coalescence for droplet collision. Unfortunately, no data were available to compare the region of rebound or the regions of the various types of sunderance. These regimes could be tested during future manned flights or during the forthcoming Space Shuttle Program (Spacelab). In formally conducted experiments a wider range of droplet sizes, impact angles, and impact velocities could be studied and better control on the droplet collision would be possible. Each experiment should also be repeated to verify the results obtained. The sequences studied in the two Skylab IV films demonstrated that valuable scientific information can be gained on the collision-coalescence process by conducting controlled droplet interactions in earth-orbiting vehicles. In the absence of strong gravitational effects, high speed camera techniques are not necessary and droplets can easily be maneuvered into positions for interactions with other droplets. By using techniques similar to those developed by the Skylab IV crew, and applying them to a wide range of physical conditions, there is a great potential for increasing the body of knowledge on droplet collision and coalescence as well as providing a better understanding of all droplet interactions.

(2) "Skylab Fluid Mechanics Drop Rotation Stability, Collisions, Eddy Mixing, and G Level," by L. R. Eaton and H. C. Wilkinson (McDonnell Douglas Astronautics Co., West, Huntington Beach, California, 92647).

Eaton and Wilkinson made the following conclusions in the analysis of Skylab experiments:

(a) The coalescence criteria of Brazier-Smith appears to hold for these drops which were on the order of centimeters in diameter. This data thus qualitatively confirms the theory.

(b) The Skylab data has shown that stable free floating drops can be produced. This procedure or one of its related methods promises to provide a measurement of interfacial surface tensions without confining containers. The method could potentially be extended to multiple fluids through a variation in the approach described by Vonnegut. Two fluids of different density could be rotated and the associated shapes could be analyzed theoretically to provide the surface tension as a function of the rotating fluid shape factors. Future experiments along this line should include photographic film as the data collection media with the provision of accurate scale factors, improved lighting, etc., to enhance image analysis. The theory for the prolate spheroid should be advanced to the state of the oblate dynamics with the inclusion of an atmosphere surrounding the drop.

(c) The fluid dynamics demonstrations have provided qualitative evaluation of the ambient acceleration level within an orbiting laboratory. This level has been shown to be significantly below $10^{-4} g_e$ that which is experienced in an earth laboratory with some events approaching $g' = 10^{-6} g_e$. An enclosed experimental environment

would ensure the lower magnitudes. In the Skylab, convection still exists due to thermal gradients and although decreased by the square root of the attenuated acceleration level, consideration must be included for this factor in the design of dynamic experiments such as drop collisions which require relative background accelerations between 10^{-4} and $10^{-6} g_e$.

- (3) "Measurements of Surface Tension of Liquids by the Vibrating Drop Technique-An Analysis of Experiments Made With Free Floating Drops Made at the Skylab IV (Days 23 and 24)," by Jorge A. Pena (Department of Meteorology, Pennsylvania State University, University Park, PA 16802).

The conclusions made by Pena are as follows:

Using the vibrating drop technique the surface tension of two different water solutions have been calculated from the film images of the experiments performed at the SKYLAB IV (Days 23 and 24). The quality of these results can be greatly improved if the experiments were designed for quantitative purposes. An accurate knowledge of the drop sizes and an improved time resolution are two areas where adjustments, easy to make, can yield not only better quality data, but also to allow to study the first stages of the oscillation where it appears that the Rayleigh equation does not hold. With all these improvements, the vibrating drop technique may become a useful tool to measure the surface tension of liquids in zero gravity conditions.

The final reports submitted by these scientists mentioned earlier have been forwarded to the office of the technical coordinator of the present contract.

One more subcontract, under the present contract, pertaining to the zero-gravity cloud chamber was granted to C. K. Liu of the University of Alabama in Tuscaloosa. The subject of this study was "Investigation of the Characteristics of Cloud Chamber Under Zero-Gravity Conditions." This final report was also forwarded to the office of the technical coordinator of the present contract.

IV. ANALYSIS OF SKYLAB FLUID MECHANICS SIMULATIONS

Studies of the dynamics of oscillation, rotation, collision and coalescence of water droplets have triggered the imagination of researchers in various fields of physical sciences, such as meteorology, nuclear physics, astrophysics, fluid mechanics, mechanical engineering and chemical engineering. Lord Rayleigh first investigated mathematically the various modes of oscillation of fluids. Since then there have been many investigators concerned with the dynamics of liquid drops, yet the mechanics of the oscillation, in particular nonlinear oscillation, rotation, in particular rotation breakup, and the coalescence processes still remain poorly understood.

To study and observe the dynamics of liquids in the terrestrial laboratory, artificial supports are required to eliminate the gravitational force and to provide the longer observational time. The levitation apparatuses which are available today are the vertical wind tunnel, electrostatic potential, high frequency acoustic waves (ultrasonic waves), and high energy level laser beams. Although these are useful techniques, their use tends to mask other types of minute forces and disturbs the original effects which might confuse the experimental observations. Experiments performed in an orbiting spacecraft with its low gravity environment offer a technique to study fluids and observe their modes of oscillation without the side effects of artificial suspension techniques.

Prior to the Skylab program various studies had been performed in wind tunnels to observe the oscillations, rotations, collision and coalescence of liquid drops. However, many of the oscillation modes could

not be detected or recorded because they were being mashed by the aerodynamic forces. To understand how water droplets will oscillate, rotate and collide, and to see how fluids will behave under the low gravity environment, a series of simple science demonstrations were proposed for the Skylab mission. The demonstrations were designed to provide a data base for the design of a fluid mechanics and a cloud physics type laboratory to be flown as a part of the Shuttle-Spacelab program. The Skylab 3 and 4 crews were requested to perform these science demonstrations so that the mechanics of collisions, coalescence, rotation, natural oscillations and techniques for manipulation and positioning of fluids in low gravity could be simulated and studied.

The hardware used in the Skylab fluid mechanics demonstrations consisted of on-board medical type syringes, pieces of tape attached to drinking straws, marker pen writing ink, grape drink, strawberry drink, pieces of thread, the teflon coated flat surface of the ED 52 "web formation in zero gravity" spider cage, reflection mirror, etc., and the on-board color TV camera. The water used in the demonstration was colored, to enhance the photography, by adding a small amount of marker pen ink, grape drink mix to each drop. Movies of the dynamics of oscillations, rotations, collisions and coalescence of water droplets under low gravity environment were recorded by on-board TV cameras. These series of color films are identified as Fluid Mechanics Demonstrations-TV 107.

In this report, our analysis of Skylab fluid mechanics simulations has resulted in four papers. The topics are

- (1) "Skylab Fluid Mechanics Demonstration: A Study of Water Droplet Oscillation in Space," Conference on Cloud Physics,

pp. 408, Am. Meteorol. Soc., Boston, Mass., 1974.

- (2) "A Zero-Gravity Demonstration of the Collision and Coalescence of Water Droplets," AIAA Paper No. 74-1256, 1974.
- (3) "An Analysis of Oscillations of Water Droplet Under Low Gravity Conditions," Proceedings of the International Colloquium on Drops and Bubbles, Ed. by D. J. Collins, M. S. Plesset, and M. M. Shaffren, Calif. Inst. Tech. and Jet Propulsion Lab., Calif., pp. 617, 1974.
- (4) "Skylab Fluid Mechanics Simulations: Oscillation, Rotation, Collision and Coalescence of Water Droplets Under Low-Gravity Environment," Space Simulation, NASA SP-379, pp. 563, NASA, Washington, D. C., 1975.

These papers are included in their entirety in the following pages.

SKYLAB FLUID MECHANICS DEMONSTRATION:
A STUDY OF WATER DROPLET OSCILLATIONS IN SPACE

O. H. Vaughan and R. E. Smith

Aerospace Environment Division
Space Sciences Laboratory
Marshall Space Flight Center, Alabama 35812

and

R. J. Hung
The University of Alabama in Huntsville
Huntsville, Alabama 35807

1. INTRODUCTION

Experiments performed in an orbiting spacecraft allow observation of phenomena which normally cannot be observed in a terrestrial laboratory. An example of such an experiment is that of the impact of two spheres of water which are not supported by a flowing column of air or held in position with encumbering supporting apparatus. Either of these two techniques tends to dampen the oscillations of the spheres of water and to mask other types of phenomena. The natural or free oscillations of water drops and other phenomena are of special interest to the cloud physicist.

The amount and rate of rain which are formed in a cloud and fall to the ground result from many interesting phenomena which occur in the life cycle of a rain shower. The initial formation of rain, from the combination of airborne nuclei and water vapor in the cloud until a full blown rain shower or intense storm has formed, is a most complex phenomenon. Over the past twenty-five years the cloud physics researchers have attempted to use the data from rainfall rate studies to arrive at a typical raindrop distribution. This drop size distribution has been used as a "fingerprint" in an attempt to identify the mechanism which created the rain. However, since there are many phenomena that occur during the creation of rain, such as rebound of drops, coalescence of drops, splintering after impacts, oscillation breakup, electrical effects, etc., which have been observed in the laboratory as well as in the field, it is still quite difficult to identify the real mechanism which will govern and control the rainfall rate. Since atmospheric microphysicists are interested in droplets, droplet interactions, and drop oscillations after impact, the Skylab 4 crew was requested to attempt to do some fluid mechanics type science demonstration during their long duration Skylab 4 mission so that natural oscillations and other phenomena of free floating water drops could be observed.

Recently, Nelson and Gokhale (1972) reported on an experimental wind tunnel study of small droplet oscillations and concluded that agree-

ment between their experimental results and the theoretical calculations as developed by Rayleigh almost 100 years ago was good. Since the range of droplet sizes they studied was much smaller than the sizes proposed in the Skylab mission, we were interested in how well the experimental data from this mission would agree with the theory.

The theoretical model used in the analysis of the flight data is based on the concept that a fluid surface tends to an equilibrium shape produced by the balance between the pressure and surface tension forces. In addition, we have also assumed that the amplitude of the oscillations is small compared with their wavelength. In the calculation of the dissipation rate we have assumed that the energy dissipation is mostly due to viscosity effects, since the rotational flow is limited only to the surface region of the water droplet, and that most of the other region of the fluid can be treated as potential flow.

The science demonstrations were performed in Skylab 4 during January 1974 by Astronaut William R. Pogue, Astronaut Jerry Carr, or Astronaut Edward Gibson acting either as an experimenter or assisting as the TV cameraman. We would like very much to express our appreciation to these people for devoting time from their busy flight timeline to perform and film these excellent demonstrations. We would also like to express our appreciation to Dr. Duncan Blanchard, State University of New York at Albany, to Dr. J. Spengler, Harvard University, and to Dr. Larry Eaton, McDonnell Douglas Astronautics Corporation for their suggestions on the various types of fluid mechanics demonstrations which might be performed in a low-gravity environment.

2. EXPERIMENTAL SET-UP

The hardware used for this demonstration consisted of on-board medical type syringes, pieces of tape attached to drinking straws, a pad of ruled paper, a mirror, marker pen writing ink, a measuring scale, and the on-board TV camera. The water used in this demonstration was colored, to enhance the photography, by adding a small amount of the marker pen ink. During the demonstration one astronaut caused the drops to

oscillate by first touching the drops on opposite sides with flats of tape mounted on the soda straws and then plucking outward while the other astronaut photographed the demonstration. The drop was caused to oscillate at its natural oscillation frequency and observed until its oscillation began to decay due to its internal damping. Thus, by observing the change in amplitude with time we were able to obtain the data required to verify the applicability of the proposed theoretical model.

3. DATA ANALYSIS TECHNIQUES

The film, taken with the 16 mm TV camera, was studied and measurements of the characteristics of the drop oscillations were made using a Vanguard film analyzer. The amplitude and wavelength of the oscillations were determined directly from the film using appropriate scale factors. The frequency of oscillations was determined by counting the number of frames that were observed during the time interval between the time that the water drop underwent deformation and returned to its original shape and then dividing this count number by the TV camera framing rate (30 frames/sec). During the demonstration we were able to observe the natural oscillations for only about 10% of the time predicted for the oscillations to dampen out completely. However, we were still able to establish a reasonable trend for the damping rate using the theoretical model and data from the film.

4. THEORETICAL MODEL

The fundamental concept of the theoretical model used in this paper is that fluid surfaces tend to an equilibrium shape produced by the balance of the forces of fluid pressure and surface tension; i.e., the pressure difference between the two sides of the fluid droplet is not zero, and it is balanced by the surface tension forces. If we assume that the amplitude of the oscillations is small compared to this wavelength, then the boundary conditions on the velocity potential ψ for rectangular coordinates can be written (Landau and Lifshitz, 1959)

$$\rho \frac{\partial^2 \psi}{\partial t^2} - \alpha \frac{\partial}{\partial z} \left(\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} \right) = 0 \text{ at } z = 0 \quad (4.1)$$

where ρ is the density of the fluid and α is the surface tension coefficient. If we consider a plane wave propagated in the direction of the x-axis, then the solution of the system can be assumed to be in the form

$$\psi = \text{Re} [A e^{-kz} e^{-i(\omega t - kx)}] \quad (4.2)$$

where A is the amplitude, k is the wave number and ω is the circular frequency of the wave. The relation between k and ω which is called the dispersion relation can be obtained by substituting equation (4.2) into the boundary condition (4.1)

$$\omega^2 = \frac{\alpha k^3}{\rho} \quad (4.3)$$

Since $\omega = 2\pi f$ where f is frequency in Hertz, we

have

$$f^2 = \frac{\alpha k^3}{4\pi^2 \rho} \quad (4.4)$$

For the case for a spherical droplet oscillation of an incompressible fluid under the action of surface tension force, the boundary condition shown in equation (4.1) in rectangular coordinates can be written into spherical coordinates as follows:

$$\rho \frac{\partial^2 \psi}{\partial z^2} - \frac{\alpha}{R^2} \left\{ 2 \frac{\partial \psi}{\partial r} + \frac{\partial}{\partial r} \left[\frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \sin \theta \frac{\partial \psi}{\partial \theta} + \frac{1}{\sin^2 \theta} \frac{\partial^2 \psi}{\partial \phi^2} \right] \right\} = 0 \text{ at } r = R \quad (4.5)$$

where the geometry of the spherical coordinates is shown in Fig. 1. If we postulate a solution in the form of a spherical wave which satisfies the spherical harmonic function of the form:

$$\psi = \text{Re} [A e^{-i\omega t} r^\ell Y_{\ell m}(\theta, \phi)] \quad (4.6)$$

with $\ell = 0, 1, 2, \dots$, and $m = 0, \pm 1, \pm 2, \pm 3, \dots$ $\pm \ell$ and using the spherical harmonic function

$$Y_{\ell m}(\theta, \phi) = P_\ell^m(\cos \theta) e^{im\phi} \quad (4.7)$$

where $P_\ell^m(\cos \theta)$ is an associated Legendre function. Then knowing that the spherical harmonics $Y_{\ell m}$ satisfies

$$\frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial Y_{\ell m}}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \frac{\partial^2 Y_{\ell m}}{\partial \phi^2} + \ell(\ell+1) Y_{\ell m} = 0 \quad (4.8)$$

we now have the relation

$$\omega^2 = \frac{\alpha \ell (\ell-1) (\ell+2)}{\rho R^3} \quad (4.9)$$

Substituting the relation $\omega = 2\pi f$, and $R = d/2$ where d is the diameter of the spherical droplet, equation (4.9) becomes

$$f^2 = \frac{2\alpha \ell (\ell-1) (\ell+2)}{\pi^2 \rho d^3} \quad (4.10)$$

which agrees with the formula obtained by Rayleigh (1945). Equation (4.10) gives the eigenfrequencies of droplet oscillation of the droplet oscillations. It can be seen that the smallest possible frequency of oscillation of the droplet corresponds to $\ell = 2$, i.e.,

$$f^2 d^3 \rho = 1.62\alpha \quad (4.11)$$

Furthermore, let us now calculate the energy dissipation of droplet oscillations. In this case the mechanical energy, E_{mech} , includes both the kinetic and the potential energy. Thus, the energy dissipated per unit time in the droplet is

$$\dot{E}_{\text{mech}} = - \int \sigma'_{ij} \frac{\partial v_j}{\partial x_j} dV \quad (4.12)$$

where σ'_{ij} is the viscous stress tensor which is defined

$$\sigma'_{ij} = \eta \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial v_l}{\partial x_l} \right) + \zeta \delta_{ij} \frac{\partial v_l}{\partial x_l} \quad (4.13)$$

and V is the volume of the fluid. Here η and ζ are called coefficients of first and second viscosity, respectively. Under the condition of an incompressible fluid (water droplet), equation (4.12) becomes

$$\dot{E}_{\text{mech}} = -\frac{1}{2} \eta \int \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)^2 dV \quad (4.14)$$

If we assume that during the oscillation of the liquid droplet the volume of the surface region of the rotational flow is small and that the velocity gradient is not large, then the existence of the region of rotational flow may be ignored. If the integration is taken over the whole volume of the fluid which moves as if it were an ideal fluid, then we have potential flow,

$$\frac{\partial v_i}{\partial x_j} = \frac{\partial^2 \psi}{\partial x_i \partial x_j} = \frac{\partial v_j}{\partial x_i} \quad (4.15)$$

so that

$$\dot{E}_{\text{mech}} = -2\eta \int \frac{\partial^2 \psi}{\partial x_i \partial x_j}^2 dV \quad (4.16)$$

In the present analysis we are not interested in the instantaneous value of energy dissipation, but the mean value of energy dissipation with respect to time. By using the definition of mean value with respect to time for periodic motion

$$\langle \psi \rangle = \frac{\omega}{2\pi} \int_0^{2\pi/\omega} \psi(\omega t) dt \quad (4.17)$$

and the wave form shown in equation (4.2), we have the mean value of mechanical energy

$$\langle \dot{E}_{\text{mech}} \rangle = -8\eta k^4 \int \langle \psi^2 \rangle dV \quad (4.18)$$

Now using the mean value of mechanical energy as

$$\begin{aligned} \langle E_{\text{mech}} \rangle &= \rho \int \langle v_i^2 \rangle dV \\ &= \rho \int \left\langle \left(\frac{\partial \psi}{\partial x_i} \right)^2 \right\rangle dV \end{aligned}$$

$$\text{whence } \langle E_{\text{mech}} \rangle = 2\rho k^2 \int \langle \psi^2 \rangle dV \quad (4.19)$$

and knowing that the energy of the wave decreases according to the law

$$\langle E_{\text{mech}} \rangle \propto e^{-2\gamma t} \quad (4.20)$$

and that the energy is proportional to the

square of the amplitude and that the amplitude decreases with time

$$A = A_0 e^{-\gamma t} \quad (4.21)$$

where A_0 is the initial value of the amplitude and γ is the damping rate of the wave. Thus, the damping rate obtained from equation (4.18) and equation (4.19) is

$$\begin{aligned} \gamma &= \frac{|\langle \dot{E}_{\text{mech}} \rangle|}{2\langle E_{\text{mech}} \rangle} \\ &= \frac{2\eta k^2}{\rho} \end{aligned} \quad (4.22)$$

5. RESULTS AND DISCUSSIONS

We were able to obtain measurements of the natural frequency of the droplet oscillations and the diameter of the droplet from the film. Using equation (4.11) which has been demonstrated to be in excellent agreement with experimental data by Nelson and Gokhale (1972), the natural frequency of the oscillations as measured, 1.66 Hertz for the contaminated water droplet which has a 2.67 cm diameter, we have calculated that the surface tension of the droplet is 32.63 dynes/cm. This surface tension value is quite low when compared to distilled water which has a surface tension value of 72 dyne/cm at 20°C. Therefore, we began to question this low value. Since we are dealing with a non-pure fluid (water contaminated with marker pen ink, Krytox oil which was used by the crew to cause minimum surface attachment of the water to the handling probes as well as other materials, e.g., potassium, chlorine, etc. to make the water potable), laboratory measurements were made here at Marshall Space Flight Center using marker pen ink and other materials (potassium, chlorine, etc.) added to a distilled water sample. Results showed that these materials reduced the surface tension value to approximately 60 dyne/cm. Surface tension measurements of Krytox show its value to be 15 dyne/cm and it appears that if minute amounts of this material became mixed with the water, it would lower its surface tension value considerably. Thus, it appears that the low surface tension value that we have obtained is reasonable since we know that the water was also contaminated with minute amounts of Krytox oil.

By using the computed surface tension value and the measured natural frequency of oscillations we obtained the wave number $k = 1.498$ or a wavelength of 4.193 cm using equation (4.4). Analysis of the film shows that two modes of oscillations were occurring and this agrees with the theoretical prediction using equation (4.10) with $\ell = 2$ as the smallest possible wave-mode oscillation. Under the similar argument with the calculated wavelength of $\lambda = 4.193$ cm and the minimum number of wave-mode, $\ell = 2$, the diameter of the droplet, $d = \ell\lambda/\pi$, becomes 2.67 cm which agrees with film measurements.

Using equation (4.22), the wave-number obtained from the previous calculations, and the

viscosity coefficient $\zeta = 0.01 \text{ cm}^2/\text{sec}$ for pure water at 20°C we computed the dissipation time for an oscillating water drop. The calculated value for the damping rate γ is 4.49×10^{-2} rad/sec or 7.146×10^{-3} Hertz while the dissipation time value becomes 139.93 seconds (2.33 minutes) or 233 cycles of oscillations. Using the initial amplitude of the droplet oscillation as measured on the film and equation (4.21), we attempted to compare the actual damping rate curve with the theoretical curve, and our results are shown in Figure 2. Although we were only able to observe the oscillations of the droplet for 13.5 seconds or 21 cycles, there is good agreement between the actual dissipation rate and the theoretical curve.

In the present analysis, the theoretical model is based on the assumption that the wave amplitude is small compared with wavelength. The experiment shows that the maximum wave amplitude is 22% of the wavelength which does not negate the theoretical assumption.

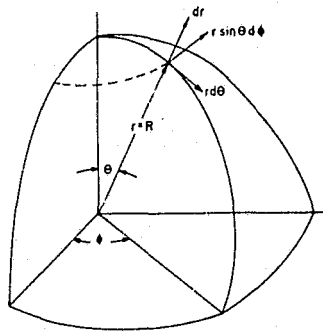


FIGURE 1: GEOMETRY OF SPHERICAL COORDINATE FOR EQUATION (4.5),

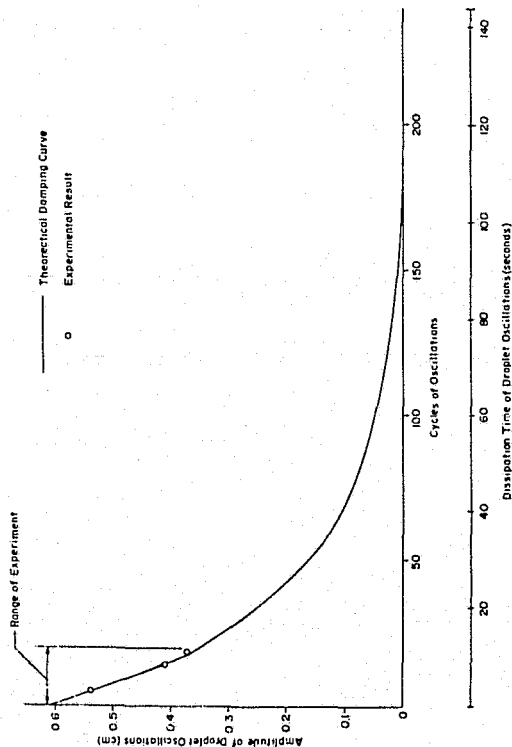


FIGURE 2: DISSIPATION OF THE AMPLITUDE WATER DROPLET OSCILLATIONS AGAINST CYCLES OF OSCILLATIONS OR DISSIPATION TIME OF DROPLET OSCILLATIONS.

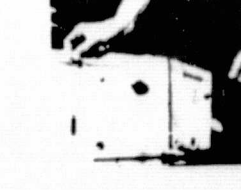
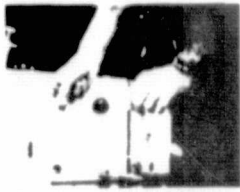
ACKNOWLEDGEMENTS

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SKYLAB 4 SCIENCE DEMONSTRATION
SELECTED SEQUENCES OF OSCILLATIONS OF A FREE FLOATING
WATER DROPLET IN A LOW GRAVITY ENVIRONMENT



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A ZERO-GRAVITY DEMONSTRATION OF THE COLLISION AND
COALESCENCE OF WATER DROPLETS

by

R. J. Hung
The University of Alabama in Huntsville
Huntsville, Alabama 35807

and

O. H. Vaughan and R. E. Smith
Orbital and Space Environment Branch/Space Sciences Lab
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

Abstract

The mechanics of the collision and coalescence of liquid droplets is one of the main research areas in the fields of nuclear physics, astrophysics, meteorology and fluid mechanics. The crew members on the Skylab 3 and 4 missions were requested to perform demonstrations of the collision and coalescence of water droplets under the low gravity environment at orbital altitude. In Skylab 4 two water droplets with equal volumes, 30 cm³ each, were used. A dark colored droplet (contaminated with grape drink) moving with a velocity of 3.14 cm/sec collided with a stationary pink colored droplet (contaminated with strawberry drink) and coalescence occurred. Theoretical models are proposed to study the various stages of the collision-coalescence processes. Special considerations are concentrated in the investigation of the bounce-coalescence and coalescence-instability processes. The surface tension of the coalesced droplets was calculated to be 52 dynes/cm in perfect agreement with laboratory measurements made by NASA/Marshall Space Flight Center after the flight using a reproduction of the liquids.

1. Introduction

The study of oscillations, collisions and coalescence of liquid drops is important to various branches of physics, such as nuclear physics, astrophysics, meteorology, and fluid mechanics. The nature of the oscillations of a liquid drop about a spheroidal shape was first investigated mathematically by Lord Rayleigh (1879). Since then, there have been many investigations of the dynamics of liquid drops, yet the mechanics of the coalescence process still remain poorly understood.

In the last forty years, studies of nuclear oscillations, fusions, and fissions, and more generally, nuclear deformation energy surfaces became one of the most interesting research topics in nuclear physics. To study these phenomena, a model of an incompressible liquid drop with charges uniformly distributed throughout the volume and a uniform surface tension is generally assumed (Cohen, et al., 1974). The focal point of this study is to trace the dynamic evolution of the axially symmetric system as a function of time and try to understand the mechanics of the fusion (or coalescence) process of the nuclear liquid drops.

In astrophysics, dynamics of liquid drops stimulate the characteristics of binary stars and rotating stars. About half the stars in the sky

are binary stars. The fission theory, proposed by Poincaré in 1885, attempted to explain the occurrence of binary stars by a natural process of evolution of a single star. In Poincaré's theory, the radiating energy distribution of the liquid mass is changing due to rotation and thus the axisymmetric liquid mass becomes highly flattened and unstable, and continues its evolution along a series of progressively more elongated ellipsoids, having a constriction in the middle. When this constriction has become deep enough, the figure consists effectively of a pair of detached masses orbiting one another. Unfortunately, by the 1920's, these problems had been worked out and the results were adverse to Poincaré's picture. Thus, the fission theory became dormant. A new fission theory of rotating liquid drops has been proposed to study these problems (Chandrasekhar, 1969).

In meteorology, all modern theories of rain formation involve the coalescence process, whereby two water drops of different sizes collide and unite to form a single layer drop. Accurate prediction of drop growth via the coalescence mechanism must ultimately depend on an understanding of the interaction between individual pairs (Mason, 1971).

To observe in the terrestrial laboratory the dynamics of liquid drops, artificial support is required to eliminate the gravitational force, thus, providing longer observational time. The levitation apparatuses available to produce vertical pressure are: (1) a vertical wind tunnel, (2) an applied electrostatic potential, (3) a high frequency acoustic wave, and (4) a high energy level laser beam. Any of the above techniques tends to dampen the oscillations of the liquid drops and mask other types of phenomena. In contrast with the experiments performed in the terrestrial laboratory, experiments in an orbiting spacecraft under low gravity conditions permit long observations of the dynamics of the liquid drops without artificial supports. Furthermore, the maximum size of the water droplets in the terrestrial laboratory is on the order of a thousand microns or less while the size of the water droplet is on the order of centimeters or more under low gravity conditions.

Because of the great advantages of having liquid drop experiments performed under a low gravity environment and because of the study of the dynamics of liquid drop being so important in the fields of nuclear physics, astrophysics, meteorology and fluid mechanics, the Skylab 3 and 4 crews were requested to perform water drop demonstrations

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during their long duration missions so that natural oscillations, and the mechanics of collisions and coalescence of water drops, could be observed.

In the present study, we have limited ourselves to studying the mechanics of collisions and coalescence of water droplets under low gravity environment performed by the Skylab 4 crew.

We would like to express our appreciation to the Skylab 4 crew members Carr, Gibson, and Pogue for performing so many interesting fluid mechanics science demonstrations.

II. Experimental Arrangements

The hardware used for this demonstration consisted of on-board medical type syringes, grape drink, strawberry drink, pieces of thread, and the on-board color TV cameras. The water used in this demonstration was colored, to enhance the photography, by adding a small amount of grape drink to make one drop dark, or by adding strawberry drink to make the other pink in color. During the demonstration, the dark colored water droplet with a velocity of 3.14 cm/sec collided with the stationary pink colored water droplet suspended on a thread and coalescence occurred. By observing the change in shape with time during the collision of these two water droplets, and change of amplitude in time after the coalescence, we were able to study the mechanics of the collision and coalescence procedures.

In the present investigation, the film taken with the on-board TV camera was studied and measurements of the characteristics of the drop collisions, coalescence, and oscillations were made using a Vanguard film analyzer. The amplitude and wavelength of the oscillations were determined directly from the film using appropriate scale factors. The frequency of oscillations was determined by counting the number of frames that were observed during the time interval that the water drop underwent deformation and returned to its original shape and then dividing this count number by the TV camera framing rate (30 frames per second).

Some selected frames of the collision and coalescence of two water drops are presented in Figure 1. The numbers on the pictures in the figure show the sequence of the TV camera frames taken during the Skylab 4 water droplet demonstration. Picture number 1 shows the dark colored droplet moving toward the stationary pink colored droplet. The volumes of the two droplets are the same, 30 cm^3 , or a sphere with a 3.85 cm diameter. Picture numbers 2 to 4 show the two droplets approaching the collision. The distances between the two droplets was greater than the critical separation distance; therefore, the two colliding droplets still kept their original shapes. Picture number 5 is at the moment when the two colliding droplets reached the critical separation distance, and suddenly the distance between two colliding droplets was bridged and coalescence then proceeded rapidly. Picture numbers 6 to 20 show how two of the coalesced droplets fused into one, and how the nonlinear wave-wave interaction oscillated in the longitudinal direction. Picture numbers 20 to 31 show how the nonlinear wave-wave interaction oscillated in the transverse direction. Picture numbers 32 to 84 show the continuous nonlinear

oscillations and how the nonlinear damping effect overcame the nonlinear growth rate. Picture numbers 85 to 151 show the typical small amplitude oscillations of a water droplet.

Analysis of these pictures frame by frame gives us an opportunity to (1) study the mechanism of the collision-coalescence processes and (2) measure the linear and nonlinear frequencies and wavelengths of the oscillations and (3) study how these oscillations decay with time.

III. Theoretical Considerations

Theoretical considerations of the coalescence problem are useful in dividing the physical processes into several distinct phases. The processes can be divided as follows:

(1) The initial action by which two drops came into close proximity in the presence of an air stream is the collision efficiency phase.

(2) When the drops are sufficiently close together they can interact and deform without actually touching, the presence of air, apparently trapped between the deformed drops, serving to keep them apart. The process of expelling this air and allowing the drops to make contact is the bounce-coalescence phase.

(3) Once contact is made, the previously separate drops become a single connected mass. In this stage, the problem is how to stabilize the subsequent oscillations of this single fluid mass and to keep it from separating into two or more fragments. This is the coalescence-instability phase.

In the past, one used to deal with the collision-coalescence problem by investigating (A) the collision efficiency, E_s , which is the ratio of the number of droplets that collide to the number in the volume swept out by the drop, (B) the coalescence efficiency, E_c , which is the fraction of the droplets that the drop collides with that coalesce with it, and (C) the collection efficiency, E , which is the ratio of the number of droplets with which the drop coalesces to the number in the volume it sweeps out. Obviously, the relation satisfies $E = E_s E_c$. The theoretical evaluation of the collision efficiency has been treated by Neiburger (1967), Shafrir and Gal-Chen (1971), Beard and Grover (1974) and many others by using the superposition technique with numerical solutions of the Navier-Stokes equations for the flow fields induced by the individual drops. The results seem well-fitted to the experimental data. As for the coalescence efficiency, it is common procedure to assume the value of unity in the past; however, the growing body of literature involving laboratory studies of water droplet interactions strongly indicates that the assumption of a coalescence efficiency of unity may be badly in error (Gun, 1965; Adam, et al., 1968; Brazier-Smith, et al., 1971). At the present time the values of the collision efficiency appears to be satisfactory, but the coalescence efficiency is almost unknown (Neiburger, et al., 1974).

The first stage of the collision-coalescence of water droplets process is the collision efficiency

one which appears to be well-understood at this moment. The combined physical processes of the second and third stages, which are the bounce-coalescence and coalescence-instability ones, respectively, in our model, used to be referred to as the coalescence efficiency problem. It is still an un-solved problem. In the present study, we limit ourselves to discussing these second and third phases of the collision-coalescence process.

Experimental studies performed by Allan, et al. (1961), MacKay and Mason (1963), and Lindblad (1964) show that the air film disappears relatively slowly as the drops collide, until a critical separation, on the order of 0.1 microns, is reached. At this moment, the film is suddenly bridged and coalescence proceeds rapidly. In the Skylab demonstrations, we were unable to see this occurrence because the frame speed of the TV camera was too slow to cover every motion of the water droplets, especially when the two droplets moved very close together.

Theoretically, to study the bounce-coalescence problem the rebound time (τ_b) and the air-film-drainage time (τ_d) for two colliding water droplets must be investigated. The criteria of bounce-coalescence are:

- (1) Rebound droplets: $\tau_b \ll \tau_d$
- (2) Partially coalescence droplets: $\tau_b \sim \tau_d$
- (3) Coalescence droplets: $\tau_b \gg \tau_d$

In general, to determine the rebound time, τ_b , and air-film-drainage time τ_d , the equations of fluid motions with the boundary conditions appropriate to such a system must be numerically integrated. The basic numerical techniques for studying transient flow problems involving an incompressible viscous fluid are those of the Marker-and-Cell (MAC) method which were developed by the Los Alamos group (Harlow and Welch, 1965). The MAC method solves the finite-difference form of Navier-Stokes equations with the velocity components and pressure defined over a staggered Eulerian mesh. The finite-difference equations for an axisymmetric geometry, which are appropriate for many drop-related problems, can be given as follows (Welch, 1966):

$$\frac{\partial u}{\partial t} + \frac{1}{r} \frac{\partial ru^2}{\partial r} + \frac{\partial uv}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial r} + \nu \frac{\partial}{\partial z} \left(\frac{\partial u}{\partial z} - \frac{\partial v}{\partial r} \right) \quad (1)$$

$$\frac{\partial v}{\partial t} + \frac{1}{r} \frac{\partial ruv}{\partial r} + \frac{\partial v^2}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - \frac{\nu}{r} \frac{\partial}{\partial r} \left[r \left(\frac{\partial u}{\partial z} - \frac{\partial v}{\partial r} \right) \right] \quad (2)$$

$$\frac{1}{r} \frac{\partial ru}{\partial r} + \frac{\partial v}{\partial z} = 0 \quad (3)$$

Here r and u are the radial coordinate and velocity, respectively, z and v the vertical coordinate and velocity, ρ the density, p the pressure and ν the kinematic viscosity.

Surface tension effects must be included in studies of drop behavior. The relation between the pressure difference, Δp , across the surface and the surface tension, α , which is given by the Young-Laplace relation, serves as the boundary condition for the problem, namely,

$$\Delta p = \alpha \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \quad (4)$$

where r_1 and r_2 denote the principal radii of the drop surface at a given point.

In addition to free surface conditions as specified in equation (4), one must apply boundary conditions at the edges of the collision. In this respect, the condition of zero tangential stress or free-slip condition is appropriate. This boundary condition essentially models the presence of a trapped air-film which drains as the drops collide.

By using the finite-difference equations (1) - (3) and the boundary conditions above, Foote (1974) calculated the rebound time for the colliding droplets. In the range of droplet diameter from 40 microns to 1190 microns, and Weber number, We , less than 4.8, the rebound time is close to the Rayleigh period τ_R . Here Weber number, We , and Rayleigh period, τ_R , are defined as

$$We = \frac{\rho d V_0^2}{\alpha} \quad (5)$$

and

$$\tau_R = \frac{\pi}{4} \left(\frac{\rho d^3}{\alpha} \right)^{1/2} \quad (6)$$

where d is the drop diameter, and V_0 is half the relative impact speed between the two colliding drops. For drop sizes greater than 1190 microns, calculations are not available at this time. As to the determination of the air-film-drainage time, theoretical calculations are totally unavailable; however, numerical computations are being done by our group now.

The third stage of the physical processes of the collision-coalescence of water droplets is the coalescence-instability problem, which is unsolved at this time, especially for the collision of two equal size droplets. We postulate that this problem may become one of the highlights in the next decade for the researchers in the fields of nuclear physics, astrophysics, meteorology and fluid mechanics.

As the oscillation of the two coalesced droplets decays gradually and the amplitude decreases, the dynamics of the droplet oscillation is governed by the boundary conditions given by the Young-Laplace relation. For the case of a small amplitude spherical droplet oscillation of an incompressible fluid under the action of a uniform surface tension force, the boundary condition shown in equation (4) can be written in spherical coordinates (Landau and Lifshitz, 1959):

$$\rho \frac{\partial^2 \psi}{\partial t^2} - \frac{\alpha}{R} \left\{ 2 \frac{\partial \psi}{\partial r} + \frac{\partial}{\partial r} \left[\frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial \psi}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \frac{\partial^2 \psi}{\partial \phi^2} \right] \right\} = 0 \quad \text{at } r = R \quad (7)$$

where ψ is the velocity potential. If we postulate

a solution in the form of a spherical wave which satisfies the spherical harmonic function of the form:

$$\psi = \text{Re} [A e^{-i\omega t} r^\ell Y_{\ell m}(\theta, \phi)] \quad (8)$$

with $\ell = 0, 1, 2, \dots$, and $m = \pm 1, \pm 2, \pm 3, \dots \pm \ell$ and using the spherical harmonic function

$$Y_{\ell m}(\theta, \phi) = P_\ell^m(\cos \theta) e^{im\phi} \quad (9)$$

where $P_\ell^m(\cos \theta)$ is an associated Legendre function, then knowing that the spherical harmonics $Y_{\ell m}$ satisfies

$$\frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial Y_{\ell m}}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \left(\frac{\partial^2 Y_{\ell m}}{\partial \phi^2} \right) + \ell(\ell+1) Y_{\ell m} = 0 \quad (10)$$

we now have the relation

$$\omega^2 = \frac{\alpha \ell (\ell-1) (\ell+2)}{\rho R^3} \quad (11)$$

which agrees with the formula obtained by Rayleigh (1879).

Equation (11) shows that $\ell=0$ and 1 correspond only to rigid body oscillations, and the fundamental mode corresponds to $\ell=2$. Equation (9) also shows that for each mode ℓ , there are $2\ell+1$ oscillations along different directions. These oscillations with the same mode ℓ have the same frequency. If we consider only the characteristics of the mode and not the type of oscillations in the various directions, the shape of the drop is

$$r = R + \sum_{\ell} a_{\ell} P_{\ell}(\cos \theta) \quad (12)$$

where P_{ℓ} is the ℓ th order Legendre polynomial, R is the radius of the unperturbed droplet, and the coefficients a_{ℓ} are functions of time:

$$a_{\ell} = \text{Re} [b_{\ell} e^{i\omega t}] \quad (13)$$

where ω is given by equation (11), and b_{ℓ} is some amplitude of the oscillations.

By expressing the amplitude of the oscillation, b_{ℓ} , in terms of the axial ratio β of the oscillating droplet, Foote (1973) gave remarkable profiles of the droplet oscillations by substituting equations (11) and (13) in equation (12). Here the axial ratio is defined as the ratio of horizontal to vertical axis length. Figure 2 shows the profiles of oscillations for various wave modes, ℓ , and axial ratios, β . Further comparisons between the Skylab experiments and the profiles of the oscillations will be discussed in the next paragraph.

IV. Results and Discussions

Studies of the collision and coalescence of liquid droplets is one of the most interesting topics among researchers in the fields of nuclear physics, astrophysics, meteorology and fluid mechanics. Physical processes of the problem used to be classified as problems of the collision efficiency and the coalescence efficiency. Much research work in the past clarified the collision efficiency problem; however, the coalescence efficiency problem still exists. In our theoretical considerations, we have suggested that the problem of coalescence efficiency be divided into bounce-coalescence and coalescence-instability problems. These two problems are involved in great amounts of numerical computations during the integration of the Navier-Stokes equations. The numerical techniques of the so-called Marker-and-Cell method which was developed by the Los Alamos group are most suitable for studying droplet dynamics. Detailed computations are now underway.

In the Skylab demonstrations, because of the restriction of the on-board instrumentations, the frame speed of the film taken during the demonstration was 30 frame/sec which made the time interval for each frame too large to cover all precise movements of the colliding water droplets. Particularly, it was very hard to check the value of the critical separation when the two droplets moved very close. However, the collision-coalescence experiments from Skylab 4 water droplet demonstrations still gave us the following significant information:

(1) The colliding water droplets kept their original shapes (no effect from the existence of other droplets) until the separation distance reached the critical value. Picture numbers 1, 2, 3, and 4 in Figure 1 verify this statement.

(2) The air film between two colliding droplets was suddenly bridged and coalescence proceeded rapidly right at the moment when two of the droplets reached the critical separation distance. Picture number 5 shows this.

(3) After the coalescence occurred, large amplitude oscillations, in which nonlinear wave-wave interactions dominated the whole process, played the most significant role in the instability of the droplet coalescence. Picture numbers 6 to 85 in Figure 1 show this mechanism.

(4) During the period of nonlinear oscillations, the wave periods for the longitudinal oscillations (e.g., picture numbers 6 to 20 in Figure 1) are apparently not the same as those for the transverse oscillations (e.g., picture number 21 to 31 in Figure 1). These changes in the droplet profiles, wavelengths, and wave frequencies during the period of nonlinear wave-wave interactions shown in the films of the Skylab 4 water droplet demonstrations offer us magnificent materials for studying the problem of coalescence-instability in the droplet collision process.

(5) After the nonlinear damping effect overcame the nonlinear growth rate, the droplet oscillations became linear wave oscillation in which most of the higher values of wave modes damped out, most likely leaving the fundamental mode, $\ell=2$, in the

oscillations.*

Items (1) and (2) above in the Skylab films show the bounce-coalescence process, while items (3) and (4) cover the coalescence-instability process. Item (5) covers the linear wave oscillations which gives us a chance to check the linear wave theory. As we have mentioned earlier, the bounce-coalescence and coalescence-instability processes are hereby involved in the integration of the Navier-Stokes equations which are used in the numerical computations and we expect to present the results of our calculations in the near future. In the Skylab 4 water droplet demonstration after the two water droplets with equal volumes collided and coalescence occurred, the oscillation frequency and wavelength were measured from films during the period after the nonlinear oscillations were suppressed. The value of the droplet oscillation frequency was 0.857 Hz. By using equation (11), the surface tension of the coalesced droplets was calculated to be 52 dynes/cm. This value of surface tension is for the water droplets contaminated with grape drink and strawberry drink while the normal surface tension for pure water at 20°C is 72 dynes/cm.

A laboratory measurement of the surface tension of a reproduction of the Skylab 4 water droplet fluids was made at the NASA/Marshall Space Flight Center, and gave a value of $\alpha = 52$ dynes/cm which is in a perfect agreement with the calculated value.

Calculations of the dissipation rate of the droplet oscillations in the period after the nonlinear oscillations were suppressed were made using equation (13) which gives $\gamma = 1.36 \times 10^{-2}$ rad/sec = 2.17×10^{-3} Hz where the viscosity coefficient $\eta = 0.01$ cm²/sec was used. This dissipation rate also agrees with the actual dissipation rate measured from the Skylab films.

In the period with linear oscillations a remarkable similarity exists between the observed profiles of the droplet oscillations in the Skylab films and the calculated profiles of an oscillating drop shown in Figure 2 obtained by Foote (1973).

*Vaughan, et al. (1974) show that the damping rate of waves, γ , is

$$\gamma = \frac{2 \eta k^2}{\rho} \quad (12)$$

where η is the viscosity coefficient, and k is the wave number. With substitutions $k = 2\pi/\lambda$ and

$\lambda = 2\pi R/\ell$ where λ is wavelength, the damping rate then becomes

$$\gamma = \frac{2 \eta \ell^2}{\rho R^2} \quad (13)$$

which shows that wave modes of higher values suffer much stronger damping than those of lower values.

In the dynamics of droplet collisions, the Weber number, which is proportional to the ratio of the drop's kinetic energy on impact, $\pi \rho d^3 v_0^2 / 12$, to its surface energy, $\alpha \pi d^2$, is a significant parameter. This implies the following characteristics: (1) As $We \gg 1$, the surface tension effects become negligible and the droplet deformation on impact becomes very great; and (2) as $We \ll 1$, inertia effects are negligible and a collision produces no significant shape changes. In the Skylab 4 water droplet demonstration, the Weber number in our particular case study is 0.18 which corresponds to the case where the inertia effect is smaller than the surface tension effect. Nevertheless, nonlinear oscillations still dominated the initial stage of the droplet coalescence process.

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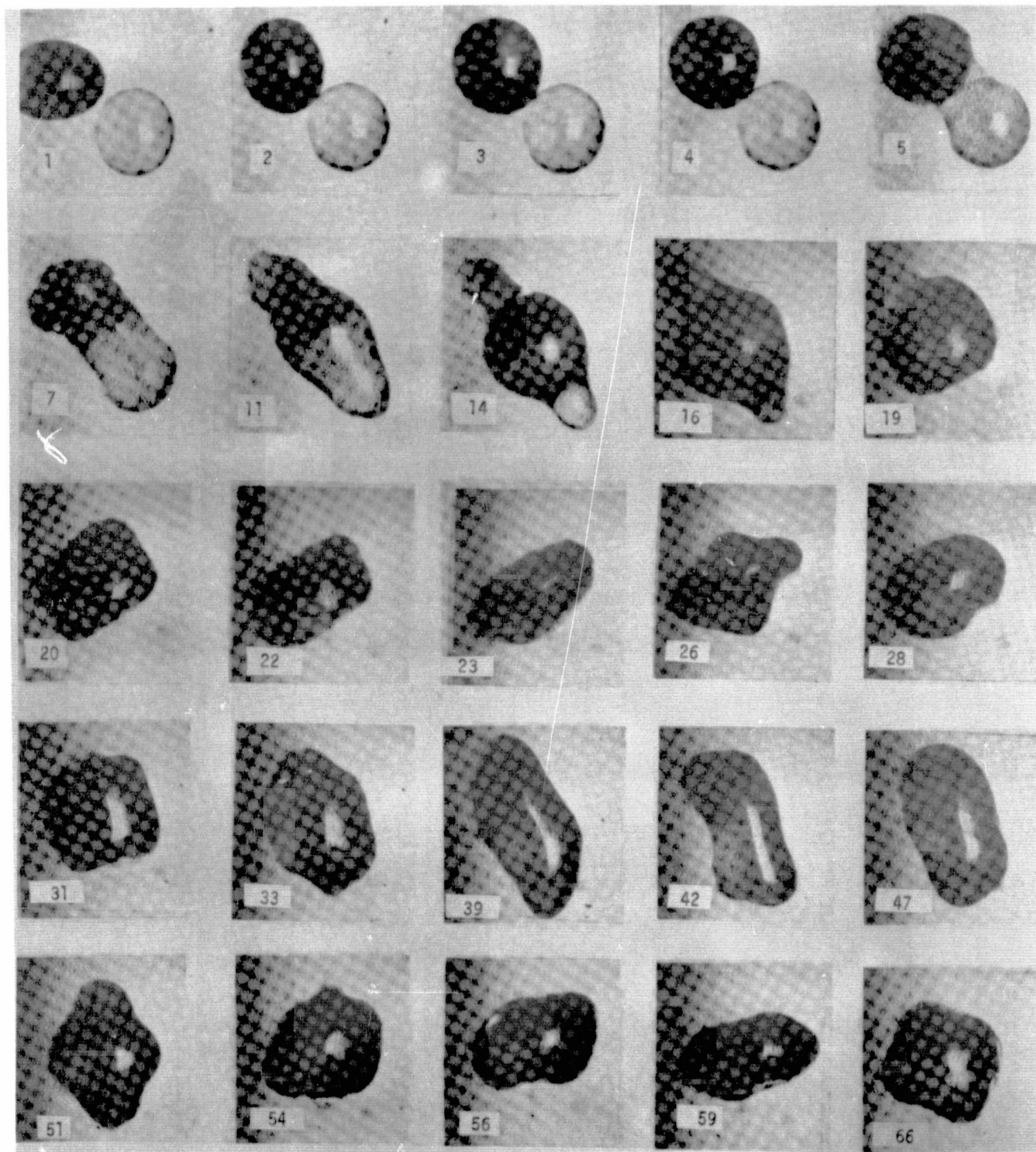
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(Figure 1 To be Continued)

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(Figure 1 Continued)

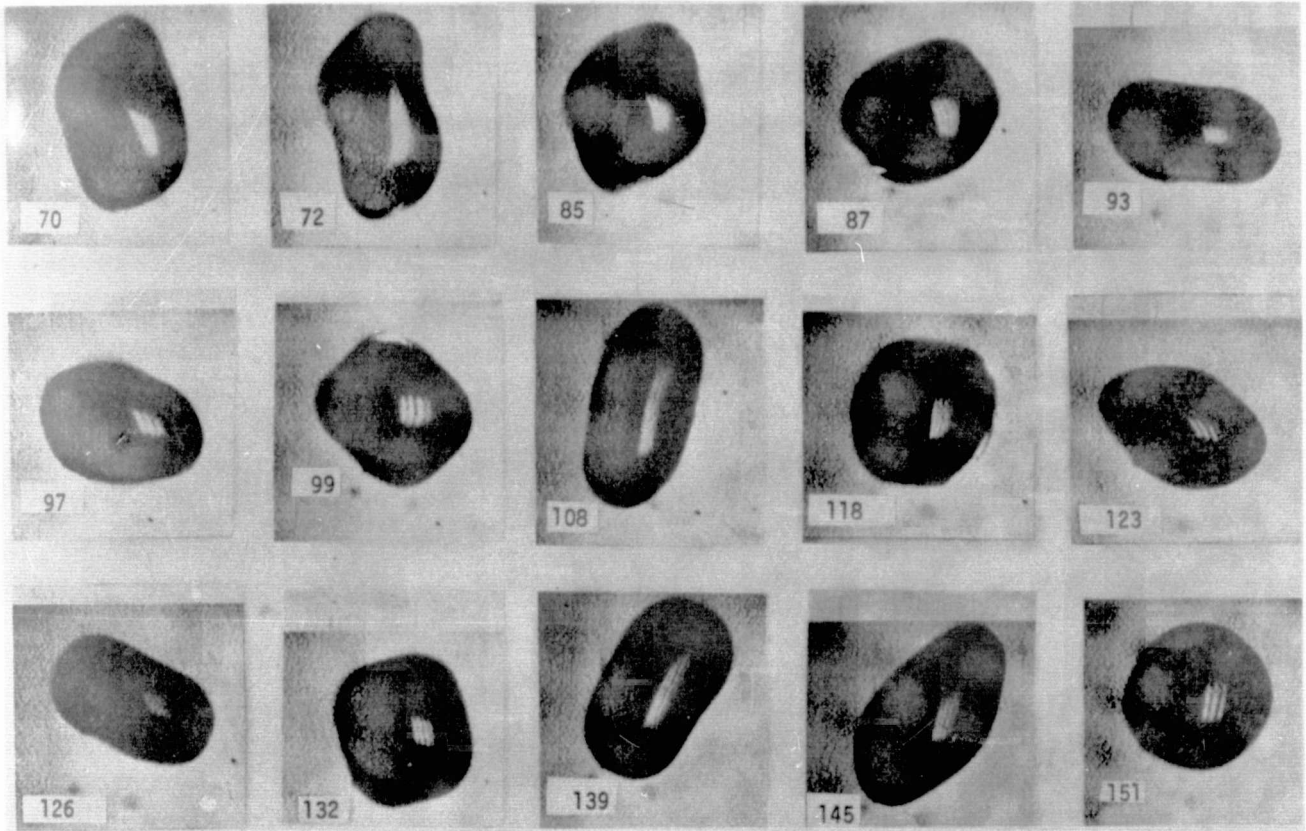


Figure 1. Selected sequences of the collision and coalescence of water droplets performed in Skylab 4 Water Droplets Demonstration under a low gravity environment.

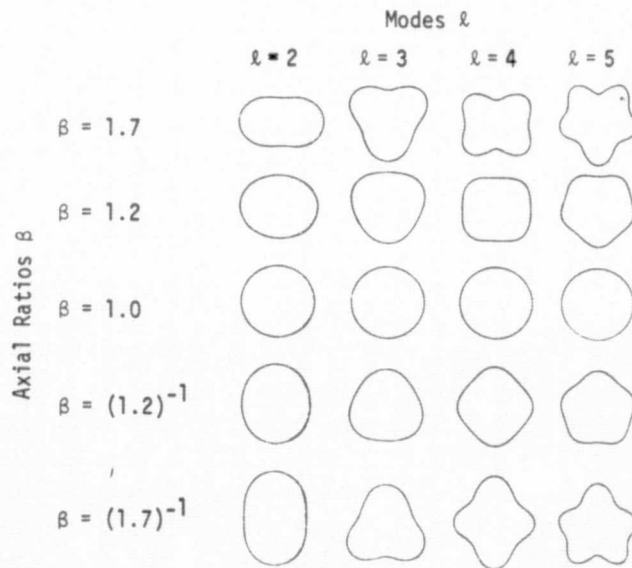


Figure 2. Profiles of Oscillating Liquid Droplet in Various Modes and Axial Ratios. (Foote, 1973)

AN ANALYSIS OF OSCILLATIONS OF A WATER DROPLET
UNDER LOW GRAVITY CONDITIONS

by

O. H. Vaughan and R. E. Smith
Aerospace Environment Division/Space Sciences Laboratory
NASA/Marshall Space Flight Center
Huntsville, Alabama 35812

and

R. J. Hung and S. T. Wu
The University of Alabama in Huntsville
Huntsville, Alabama 35807

ABSTRACT

Astronaut William R. Pogue conducted some water droplet oscillation demonstrations on the Skylab 4 mission in low earth orbit. In one of the demonstrations he used a soda straw to cause the droplet, attached to a flat plate, to oscillate. Marker pen ink was added to the droplet to enhance photography using an on-board TV camera. The drop, which was 2.54 cm high and 3.52 cm wide, was observed to have a natural oscillation frequency of 1.3 Hz. The demonstration was photographed with an on-board TV camera to record the oscillation of the droplet and dissipation. We were able to obtain excellent data on the change in amplitude with time from the observations. An analysis was performed using these photographic data and a theoretical model was developed for determining the oscillation frequency, wavelength, surface tension and damping characteristics of the water droplet when attached to a flat plate. The theoretical model and these observation data are in good agreement.

I. INTRODUCTION

Experiments performed in an orbiting spacecraft under low gravity conditions allow observations of phenomena which normally cannot be done in a terrestrial laboratory. An example of such an observation is that of the impact of two spheres of water which are not supported by either an aerodynamic force due to a flowing column of air or held in position with an encumbering supporting apparatus. Either of these two techniques tends to dampen the oscillations of the spheres of water and to mask other types of phenomena. The natural or free oscillations of water drops and other phenomena are of special interest to the cloud physicist and other fluid mechanics researchers.

Atmospheric microphysics deals with droplet and droplet-droplet interactions. Particularly, the mechanisms which occur during the creation of rain, such as the rebound of drops, coalescence of drops, splintering after impacts, oscillation breakup, electrical effects, etc., are all of special interest. To study these mechanisms, the Skylab 4 crew was requested to do some fluid mechanics type science demonstrations during their long duration mission so that natural oscillations and other phenomena of water droplets could be observed.

This paper presents results of a demonstration conducted by astronaut William R. Pogue to study water droplet oscillations in low earth orbit. In this demonstration he perturbed a droplet, attached to a flat surface, and caused it to oscillate. The droplet had been contaminated with marker pen ink to enhance it for photography using an on-board TV camera. An analysis was performed using this photographic data and a theoretical model was developed to determine the oscillation frequency, wavelength, surface tension and damping characteristics of the water droplet attached to a flat plate. A comparison between laboratory surface tension and experiment and the value calculated from this experimental observation was made with good agreement.

II. EXPERIMENTAL ARRANGEMENTS

The hardware used for this demonstration consisted of on-board medical type syringes, pieces of tape attached to drinking straws, a pad of ruled paper, marker pen writing ink, the teflon coated flat surface of the ED 52 "Web formation in zero gravity" spider cage, and the on-board TV camera. The water used in this demonstration was colored, to enhance the photography, by adding a small amount of the marker pen ink. During the demonstration a water droplet, attached to a flat surface, was caused to oscillate by motion of a soda straw. By observing the change in amplitude with time we were able to obtain the data required to verify the applicability of a proposed theoretical model.

In the present investigation, the film, taken with the on-board TV camera, was studied and measurements of the characteristics of the drop oscillations were made using a Vanguard film analyzer. The amplitude and wavelength of the oscillations were determined directly from the film using appropriate scale factors. The frequency of oscillations was

determined by counting the number of frames that were observed during the time interval between the time that the water drop underwent deformation and returned to its original shape and then dividing this count number by the TV camera framing rate (30 frames/sec).

Some selected frames of the various modes of the oscillating water droplet attached to the flat surface are presented in Figure 1. The numbers on the pictures in the figure show the sequence of TV camera frames taken in the Skylab demonstration. Picture number 1 is at the moment when a drinking straw was inserted into the center of the water drop attached to the flat surface. Picture numbers 4, 6, 9 and 12 show the soda straw being pulled out of the water drop, and picture number 13 shows the moment when the soda straw left the surface of the water drop. Picture number 14 shows the oscillation of the water drop at its maximum amplitude right after the soda straw completely left the surface of the drop while picture number 28 shows the drop at its minimum amplitude. Picture numbers 30, 33, 34, 35, 36, 37 and 38 show how the water drop increased its amplitude again and picture number 40 shows the moment when the water drop just completed one cycle of oscillation and returned to its maximum amplitude.

Analysis of these pictures frame by frame give us an opportunity to measure the frequency and wavelength of the oscillations and how these oscillations decay with time.

III, THEORETICAL MODEL

A theoretical calculation for the oscillation of free floating liquid droplet was given by Lord Rayleigh (1879) almost a hundred years ago. Recently, Nelson and Gokhale (1972) reported an experimental study of small amplitude natural droplet oscillations with droplet sizes from a few hundred micrometers to millimeters in a vertical wind tunnel study, and concluded that the agreement between experimental results and theoretical calculation given by Rayleigh was good. The present study concerns oscillations of a water droplet attached to a flat plate rather than oscillations of a free floating droplet, and the size of the droplet is several cm rather than a hundred μm . It is interesting to study the present experiment to see how well the data agrees with theoretical models.

The theoretical model is based on the concept that fluid surfaces tend to be in equilibrium when the surface tension forces are balanced by the fluid pressure. If we assume that the amplitude of the oscillations is small compared to the wavelength, then the boundary conditions on the velocity potential ψ for the rectangular coordinates can be written (Landau and Lifshitz, 1959)

$$\rho \frac{\partial^2 \psi}{\partial t^2} - \alpha \frac{\partial}{\partial z} \left(\frac{\partial^2 \psi}{\partial x^2} \quad \frac{\partial^2 \psi}{\partial y^2} \right) = 0 \quad \text{at } z = 0 \quad (3.1)$$

where ρ is the density of the fluid and α is the surface tension coefficient. If we consider a plane wave propagated along the x-axis, then the solution of the system can be assumed to be in the form

$$\psi = \text{Re} \left[A e^{-kz} e^{-i(\omega t - kx)} \right] \quad (3.2)$$

where A is the amplitude, k is the wave number, and ω is the circular frequency of the wave. The relation between k and ω which is called the dispersion relation can be obtained by substituting Equation (3.2) into the boundary condition (3.1)

$$\omega^2 = \frac{\alpha k^3}{\rho} \quad (3.3)$$

Since $\omega = 2\pi f$ where f is the oscillation wave frequency in Hz, we have

$$f^2 = \frac{\alpha k^3}{4\pi^2 \rho} \quad (3.4)$$

It is important to point out that a plane wave solution as we have shown in equation (3.2) may not be true when the radius of curvature of the oscillating fluid is on the order of the wavelength of the oscillations. In this case, spherical harmonics rather than a plane wave solution is more suitable for describing the oscillation of the droplet. For the case of a spherical droplet oscillation of an incompressible fluid under the action of surface tension force, the boundary condition shown in equation (3.1) in rectangular coordinates can be written into spherical coordinates as follows:

$$\rho \frac{\partial^2 \psi}{\partial t^2} - \frac{\alpha}{R^2} \left\{ 2 \frac{\partial \psi}{\partial r} + \frac{\partial}{\partial r} \left[\frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial \psi}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \frac{\partial^2 \psi}{\partial \phi^2} \right] \right\} = 0 \quad \text{at } r = R \quad (3.5)$$

If we postulate a solution in the form of a spherical wave which satisfies the spherical harmonic function of the form:

$$\psi = \text{Re} \left[A e^{-i\omega t} r^\ell Y_{\ell m}(\theta, \phi) \right] \quad (3.6)$$

with $\ell = 0, 1, 2, \dots$, and m, $\pm 1, \pm 2, \pm 3, \dots, \pm \ell$ and using the spherical harmonic function

$$Y_{\ell m}(\theta, \phi) = P_{\ell}^m(\cos \theta) e^{im\phi} \quad (3.7)$$

where $P_{\ell}^m(\cos \theta)$ is an associated Legendre function. Then knowing that the spherical harmonics $Y_{\ell m}$ satisfies

$$\frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial Y_{\ell m}}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \left(\frac{\partial^2 Y_{\ell m}}{\partial \phi^2} \right) + \ell(\ell+1) Y_{\ell m} = 0 \quad (3.8)$$

we now have the relation

$$\omega^2 = \frac{\alpha \ell(\ell-1)(\ell+2)}{\rho R^3} \quad (3.9)$$

Substituting the relations $\omega = 2\pi f$, and $R = d/2$, where d is the diameter of the spherical droplet, equation (3.9) becomes

$$f^2 = \frac{2 \alpha \ell(\ell-1)(\ell+2)}{\pi^2 \rho d^3} \quad (3.10)$$

which agrees with the formula obtained by Rayleigh (1879).

It is clear that the fundamental mode of the spherical harmonic oscillations is $\ell=2$. In the present study, the wave mode of oscillation observed for the water droplet attached to the flat surface is a single mode which is equivalent to $\ell=2$ for the spherical harmonic case. By making a comparison between equations (3.4) and (3.10) and substituting $k = 2\pi/\lambda$ and $\lambda = \pi d/2$ in equation (3.4), we find that the plane wave solution and the spherical harmonic solution are equivalent for $\ell=2$. For the case of multi-modes oscillations derivations between the plane wave solution and spherical harmonic solution becomes apparent. Table I shows the percentage deviation between these two solutions. The maximum deviation shown is 11% when $\ell=4$ with the deviation gradually decreasing as ℓ increases.

In the present study, the contact angle between the water droplet and the flat surface is close to $\pi/2$, and there is no indication shown in the film obtained from Skylab that the contact line between the fluid and solid surface moved as the water droplet oscillated. This is the fundamental assumption we have made for boundary conditions in which we assume that the velocity potential vanishes on the contact line. If the contact line moves, a special justification is necessary (West, 1911; Huh and Scriven, 1971).

Physically, the surface tension α is a measure of the work done per unit area to balance the pressure difference between the two sides of the fluid. This implies that α increases when the pressure difference increases, and α decreases when the fluid is contaminated with impurities.

Furthermore, let us now calculate the energy dissipation of droplet oscillations. In this case the mechanical energy, E_{mech} , includes both the kinetic and the potential energy. Thus, the energy dissipated per unit time in the droplet is

$$\dot{E}_{\text{mech}} = - \int \sigma'_{ij} \frac{\partial v_j}{\partial x_j} dV \quad (3.11)$$

where σ'_{ij} is the viscous stress tensor which is defined

$$\sigma'_{ij} = \eta \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial v_l}{\partial x_l} \right) + \zeta \delta_{ij} \frac{\partial v_l}{\partial x_l} \quad (3.12)$$

and v is the velocity and V is the volume of the fluid. Here η and ζ are called coefficients of first and second viscosity, respectively. Under the condition of an incompressible fluid (water droplet), equation (3.11) becomes

$$\dot{E}_{\text{mech}} = - \frac{1}{2} \eta \int \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)^2 dV \quad (3.13)$$

If we assume that during the oscillation of the liquid droplet the volume of the surface region of the rotational flow is small and that the velocity gradient is not large, then the existence of the region of rotational flow may be ignored. If the integration is taken over the whole volume of the fluid which moves as if it were an ideal fluid, then we have potential flow,

$$\frac{\partial v_i}{\partial x_j} = \frac{\partial^2 \psi}{\partial x_i \partial x_j} = \frac{\partial v_j}{\partial x_i} \quad (3.14)$$

so that

$$\dot{E}_{\text{mech}} = -2\eta \int \left(\frac{\partial^2 \psi}{\partial x_i \partial x_j} \right)^2 dV. \quad (3.15)$$

In the present analysis we are not interested in the instantaneous value of energy dissipation, but the mean value of energy dissipation with respect to time. By using the definition of mean value with respect to time for periodic motion

$$\langle \psi \rangle = \frac{\omega}{2\pi} \int_0^{\frac{2\pi}{\omega}} \psi(\omega t) dt \quad (3.16)$$

and the wave form shown in equation (3.2), we have the mean value of mechanical energy

$$\langle \dot{E}_{\text{mech}} \rangle = -8\eta k^4 \int \langle \psi^2 \rangle dV . \quad (3.17)$$

Now, the mean value of mechanical energy is

$$\begin{aligned} \langle E_{\text{mech}} \rangle &= \rho \int \langle v_i^2 \rangle dV \\ &= \rho \int \langle \left(\frac{\partial \psi}{\partial x_i} \right)^2 \rangle dV \end{aligned}$$

whence

$$\langle E_{\text{mech}} \rangle = 2\rho k^2 \int \langle \psi^2 \rangle dV . \quad (3.18)$$

It is known that the energy of the wave decreases according to the law

$$\langle E_{\text{mech}} \rangle \propto e^{-2\gamma t} \quad (3.19)$$

since the energy is proportional to the square of the amplitude where the amplitude decreases with time as

$$A = A_0 e^{-\gamma t} \quad (3.20)$$

Here A_0 is the initial value of the amplitude and γ is the damping rate of the wave. Thus, the damping rate obtained from equations (3.17) and (3.18) is

$$\begin{aligned} \gamma &= \frac{|\langle \dot{E}_{\text{mech}} \rangle|}{2\langle E_{\text{mech}} \rangle} \\ &= \frac{2\eta k^2}{\rho} \end{aligned} \quad (3.21)$$

IV. RESULTS AND DISCUSSIONS

We were able to obtain measurements of the natural frequency of the oscillations of the droplet attached to a flat surface, and the size of the droplet from the film. As we have stated earlier, the phenomena of fluid-solid contact line is always a problem when contact line moves (Huh and Scriven, 1971). This is because the movement of fluid-solid

contact line violates the basic boundary conditions. Fortunately, after careful examination of Skylab films, we found that there is no indication that the contact line between the fluid and solid surface moved when the water droplet oscillated in the present case. The natural frequency of the oscillations as measured was 1.3 Hz for the contaminated water droplet (2.54 cm in height and 3.52 cm in width) attached to a flat surface. By using the observed natural frequency and wavelength, $\lambda (\equiv 2\pi/k) = 6.1$ cm, determined from the Skylab demonstration film, the surface tension of the droplet oscillation can be obtained from the following relation based on equation (3.4) or equation (3.10) with $\ell = 2$

$$\alpha = \frac{f^2 \lambda^3 \rho}{2\pi} \quad (4.1)$$

$$= 61 \text{ dynes/cm.}$$

This value is for the surface tension for water contaminated with marker pen ink while the surface tension for pure water at 20° C is 72 dynes/cm.

A laboratory measurement of the surface tension of a reproduction of the Skylab water which is contaminated with marker pen ink was made at the NASA/Marshall Space Flight Center and gave a value of $\alpha = 60$ dynes/cm which is in good agreement with Skylab demonstration value.

Calculation of the dissipation rate of the droplet oscillation is rather straightforward by substituting the observed wave number in equation (3.21). It is

$$\gamma = 2.05 \times 10^{-2} \text{ rad/sec} \quad (4.2)$$

$$= 3.26 \times 10^{-3} \text{ Hz}$$

when the viscosity coefficient of pure water at 20° C is used ($\eta = 0.01$ cm²/sec). This damping rate of the droplet oscillation corresponds to a dissipation time of 306 seconds.

Using the initial amplitude of the droplet oscillations as measured on the film and equation (3.20), we attempted to compare the actual damping rate curve with a theoretical curve, and our results are shown in the Figure 2. Although we were only able to observe the oscillations of the droplet for 22 seconds, there is good agreement between the actual dissipation rate and the theoretical curve.

In the present analysis, the theoretical model is based on the assumption that the wave amplitude is small compared with the wavelength. The maximum amplitude of the droplet oscillation is 7% of the wavelength which substantiates the validity of the assumptions used in the development of the theoretical model.

ACKNOWLEDGEMENT

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TABLE 1
 COMPARISON OF THE PLANE WAVE SOLUTION AND
 SPHERICAL HARMONIC SOLUTION

Mode (λ)	Deviation*
2	0.0
4	0.11
6	0.10
8	0.085
10	0.080
12	0.065
15	0.055
20	0.043
30	0.030
50	0.018
80	0.012
100	0.009

$$*Deviation = \frac{f^2]_{plane\ wave} - f^2]_{spherical\ harmonic}}{f^2]_{plane\ wave}}$$

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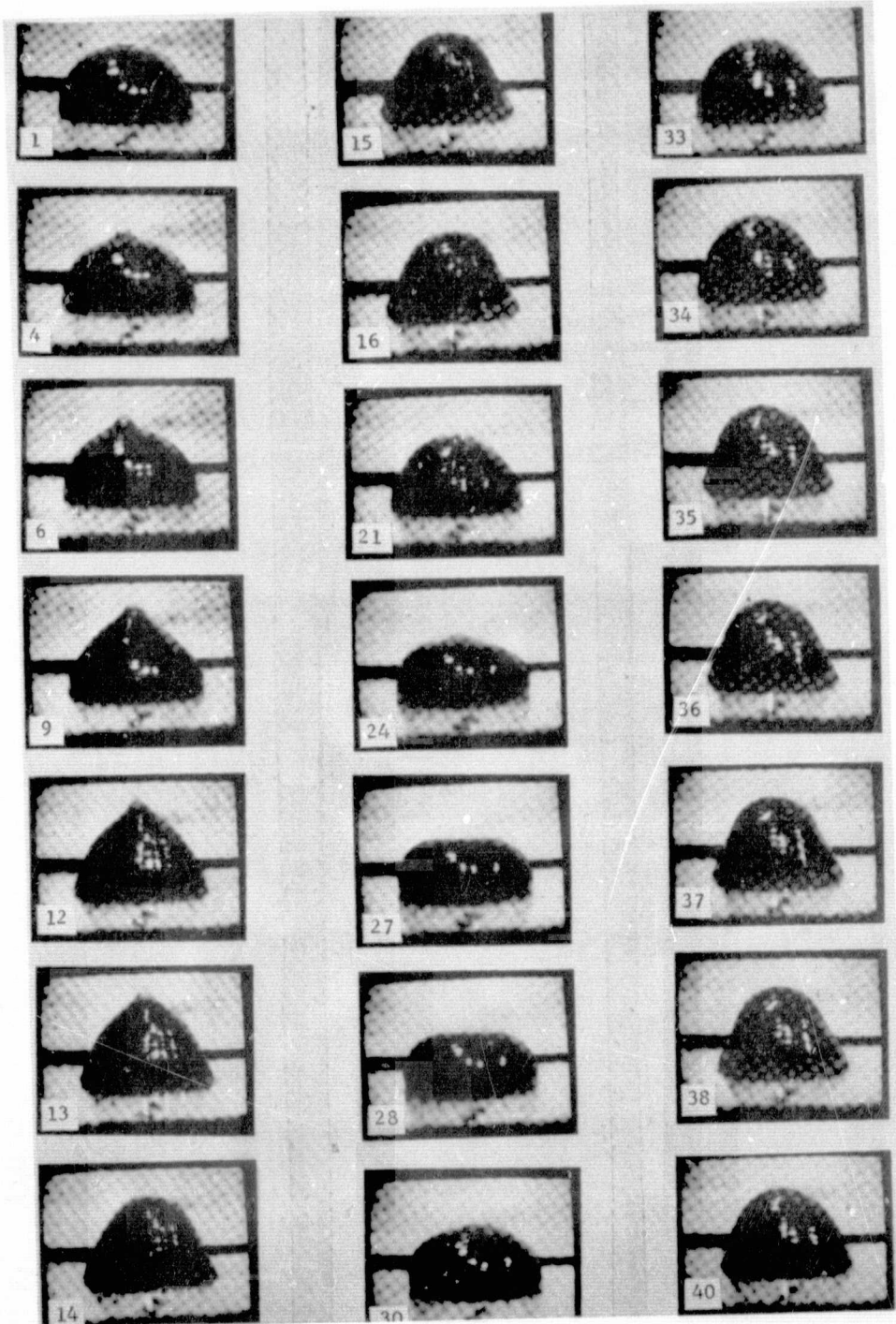


Fig. 1. Skylab 4 Science Demonstrations of Selected Sequences of the Oscillating Water Droplet Attached to the Flat Surfaces in a Low Gravity Environment.

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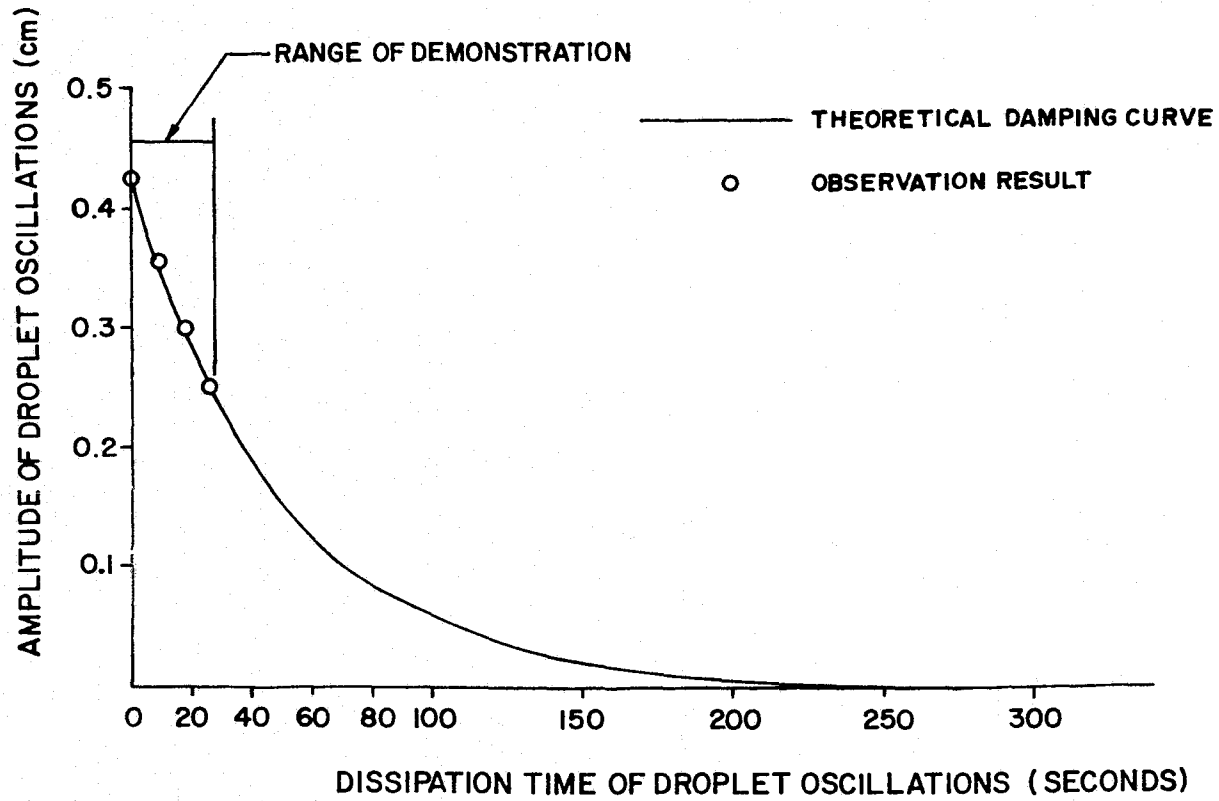


Fig. 2. Dissipation of the Amplitude of Droplet Oscillations Against Dissipation Time of Droplet Oscillations,

SKYLAB FLUID MECHANICS SIMULATIONS: OSCILLATION, ROTATION, COLLISION AND COALESCENCE OF WATER DROPLETS UNDER LOW-GRAVITY ENVIRONMENT

Otha H. Vaughan, Jr., *Aerospace Environment Div./Space Sciences Lab., NASA/Marshall Space Flight Center, Alabama 35812*

R. J. Hung, *The University of Alabama in Huntsville, Alabama 35807*

ABSTRACT

Studies of the dynamics of water droplets has been one of the most interesting areas in the fields of atmospheric microphysics, nuclear physics, astrophysics, fluid mechanics, mechanical engineering, and chemical engineering. Skylab 4 crew members performed a series of demonstrations showing the oscillations, rotations, as well as collision coalescence of water droplets which simulate various physical models of fluids under low gravity environment. The results from Skylab demonstrations show that these demonstrations have provided much interesting information and illustrate the potential of an orbiting space-oriented research laboratory for the study of more sophisticated fluid mechanic experiments.

I. INTRODUCTION

Recently, the dynamics of oscillation, rotation, collision and coalescence of water droplets has triggered the imagination of researchers in various fields of physical sciences, such as meteorology, nuclear physics, astrophysics, fluid mechanics, mechanical engineering and chemical engineering. Lord Rayleigh (1879) first investigated mathematically the various modes of oscillation of fluids. Since then there have been many investigations concerning the dynamics of liquid drops, yet the mechanics of the oscillation (particularly nonlinear oscillation), rotation (particularly rotation breakup), and the coalescence processes still remain poorly understood.

To study and observe the dynamics of liquids in the terrestrial laboratory, artificial supports are required to eliminate the gravitational force and to provide for longer observational time. The levitation apparatuses which are available today are the vertical wind tunnel, electrostatic potential, high frequency acoustic waves (ultrasonic waves), and high energy level laser beams. Although these are useful techniques, their use tends to mask other types of minute forces and disturbs their effects which might confuse the experimental

observations. Experiments performed in an orbiting spacecraft with its low gravity environment offer a technique to study fluids and observe their modes of oscillation without the side effects of artificial suspension techniques.

Prior to the Skylab program various studies had been performed in wind tunnels to observe the oscillations, rotations and coalescence of liquid drops (e.g., Beard and Pruppacher, 1971). However, many of the oscillation modes could not be detected or recorded because they were being masked by the aerodynamic forces. To understand how water droplets will oscillate, rotate and collide, and to see how fluids will behave under the low gravity environment, a series of simple science demonstrations were proposed for the Skylab mission. The demonstrations were designed to provide a data base for the design of a fluid mechanics and a cloud physics type laboratory to be flown as a part of the Spacelab Shuttle program. The Skylab 3 and 4 crews were requested to perform these science demonstrations so that the mechanics of collisions, coalescence, rotation, natural oscillations and techniques for manipulation and positioning of fluids in low gravity could be simulated and studied.

In the present paper, we have limited ourselves to a discussion of the following three branches of fluid mechanics simulation under low-gravity environment: (1) oscillation of droplet which characterizes the nuclear oscillation in nuclear physics, bubble oscillation of two phase flow in chemical engineering, and water drop oscillation in meteorology; (2) rotation of droplet which characterizes nuclear fission in nuclear physics, formation of binary stars and rotating stars in astrophysics, and breakup of water droplet in meteorology; and (3) collision and coalescence of droplets which characterize nuclear fusion in nuclear physics, and processes of rain formation in meteorology.

II. EXPERIMENTAL ARRANGEMENTS

The hardware used in the Skylab fluid mechanics demonstrations consisted of on-board medical type syringes, pieces of tape attached to drinking straws, marker pen writing ink, grape drink, strawberry drink, pieces of thread, the teflon coated flat surface of the ED 52 "web formation in zero gravity" spider cage, reflection mirror, etc., and the on-board color TV camera. The water used in the demonstration was colored, to enhance the photography, by adding a small amount of marker pen ink, grape drink mix, or strawberry drink mix to each drop. Movies of the dynamics of oscillations, rotations, collisions and coalescence of water droplets under low gravity environment were recorded on-board TV cameras. These series of color films are identified as Fluid Mechanics Demonstrations - TV 107.

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The films taken with the on-board TV cameras were later analyzed. Measurements of the characteristics of the drop oscillations, rotations, collisions and coalescence were made by using a Vanguard film analyzer. The amplitude and wavelength of the oscillations were determined directly from the film using appropriate scale factors. The frequency of oscillation and angular velocity of rotation were determined by counting the number of frames that were observed during the time interval and then dividing this count number by the TV camera framing rate.

In this paper, techniques and results of space simulation will be discussed. The theoretical analysis and comparison of the Skylab demonstration data with existing theory is out of the scope of the paper but it is published elsewhere (Vaughan, et al., 1974a; Vaughan, et al., 1974b; Hung, et al., 1974).

III. SKYLAB FLUID MECHANICS SIMULATIONS

The Skylab science demonstration/simulation TV 107 (Fluid Mechanics Demonstration) has created much interest among the researchers in various fields, such as meteorology, nuclear physics, astrophysics, fluid mechanics, mechanical engineering and chemical engineering. In particular, fluid demonstration of oscillation, rotation, collision and coalescence of water droplets simulate some physical models of interests which may contribute toward the solutions of a great number of unsolved problems.

Some selected frames of oscillation, rotation, collision and coalescence of water droplets from TV 107 will be presented in this paper.

A. Oscillation of Water Droplet - Study of nuclear oscillations has been one of the major topics in nuclear physics in the last forty years. In particular, nuclear physicists are mostly interested in the investigation of nuclear deformation energy surfaces. To study these phenomena, a model of an incompressible liquid drop with charges uniformly distributed throughout the volume and a uniform surface tension is generally assumed (Cohen, et. al., 1974).

Atmospheric microphysics studies deals with droplet and droplet-droplet interactions. Particularly, oscillation of water droplet and oscillation breakup of droplet are closely correlated to the mechanism of rain formation (Mason, 1971).

Stability of bubble oscillation is very important for the study of two-phase flow in chemical engineering. Furthermore, chemical engineers are also very interested in the study of the dynamics of the contact line between the fluid and solid surface as the water droplet oscillated (West, 1911; Huh and Scriven, 1971).

These physical models of interests were very well simulated and are shown in the Skylab Fluid Mechanics Simulation. Figure 1 shows some selected frames of the various modes of water droplet oscillation. The numbers on the pictures in the figure show the

sequence of TV camera frames taken in the Skylab demonstration. Picture number 1 shows a water droplet with the diameter of 2.67 cm touched on opposite sides by two soda straws. Picture number 7 shows that two soda straws were plucked outward from the water droplet causing the water droplet to oscillate. We observe various modes of oscillation until the decay of oscillation occurs due to its internal damping. Picture number 9 shows the oscillation of a water droplet in longitudinal direction and picture 17 indicates the oscillation of a water droplet in transverse direction. Pictures number 22 and 24 show the transition of droplet oscillation from transverse direction to longitudinal direction. Pictures number 33 and 36 show the transition of droplet oscillation from longitudinal to transverse direction. Picture number 42 shows the recovery of the oscillation of a water droplet to its original shape due to damping effect.

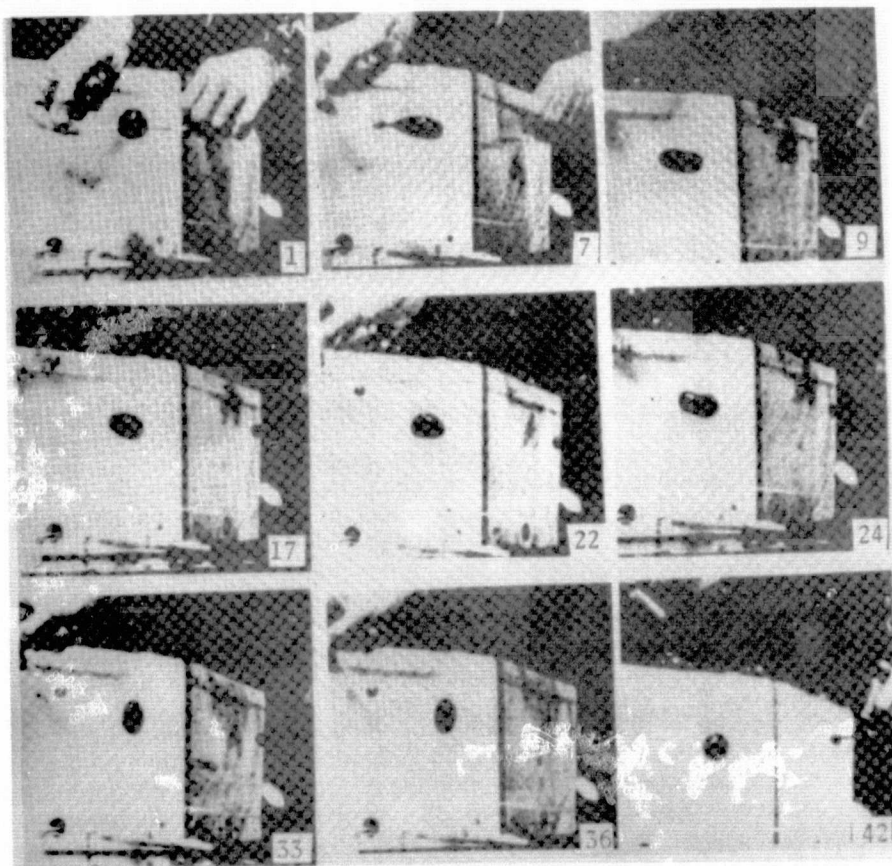


Figure 1. Skylab Fluid Mechanics Demonstration - Free Oscillation of Water Droplet.

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Figure 2 shows selected frames of the various modes of the oscillating water droplet attached to the flat surface. This is very useful for the study of droplet oscillations and the dynamics of contact line between the fluid and solid surface as the water droplet oscillated. Picture number 1 shows a drinking straw being inserted into the center of a water droplet attached to the flat surface. Pictures number 3 and 10 show the soda straw being pulled out of the water drop. Picture number 17 shows the oscillation of water droplet as it reaches its maximum amplitude right after the soda straw left the surface of the droplet. Pictures number 22 and 26 shows the water droplet decreasing its amplitude, and picture number 29 shows the oscillation of a water droplet descending to its minimum amplitude. Picture number 31 shows the increasing amplitude of a water droplet, and picture number 39 shows the proximate moment when the water droplet just completed one cycle of oscillation and returned to its maximum amplitude.

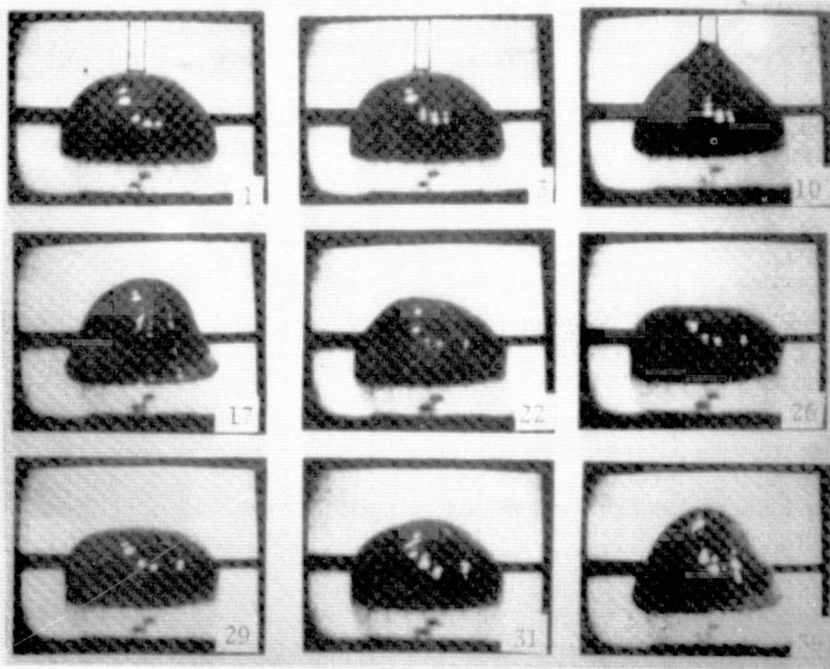


Figure 2. Skylab Fluid Mechanics Demonstration - Oscillation of Water Droplet Attached to the Flat Surface.

The dynamics of the droplet oscillation is governed by the boundary condition given by the Young-Laplace relation (Landau and Lifshitz, 1959). Solution of Young-Laplace relation leads to the relation of droplet oscillation (Rayleigh, 1879)

$$\omega^2 = \frac{\alpha l (l-1) (l+2)}{\rho R^3} \quad (1)$$

where α denotes surface tension; ρ , the density of fluid; R , the radius of unperturbed liquid droplet; ω , the circular frequency of oscillation; and $\ell = 0, 1, 2, \dots$, the integer numbers. Equation (1) shows that $\ell = 0$ and 1 correspond only to rigid body oscillations, and the fundamental mode corresponds to $\ell = 2$. In general, the oscillation for each mode ℓ , there are $2\ell + 1$ oscillations along different directions. These oscillations with the same mode ℓ have the same frequency. If we consider only the characteristics of the mode and not the type of oscillations in the various directions, the shape of the drop is (Hung, et al., 1974)

$$r = R + \sum_{\ell} a_{\ell} P_{\ell}(\cos \theta) \quad (2)$$

where P_{ℓ} is the ℓ th order Legendre polynomial; (r, θ, ϕ) , the axes of spherical coordinates; and the coefficients a_{ℓ} are functions of time t :

$$a_{\ell} = R e [b_{\ell} e^{-i\omega t}] \quad (3)$$

where ω is given by Equation (1), and b_{ℓ} is some amplitude of the oscillations.

Skylab Fluid Mechanics Demonstration provides us a good opportunity to study how well the theory stands.

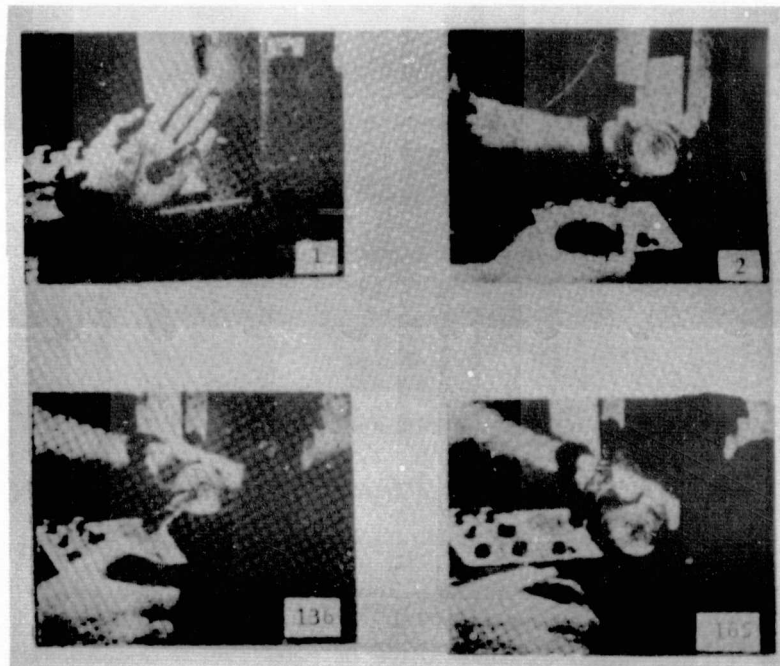
B. Rotation of Water Droplet - About half the stars in the sky are binary stars. The fission theory, proposed by Poincaré in 1885, attempted to explain the occurrence of binary stars by a natural process of evolution of a single star. Unfortunately, recent investigation showed that the results were adverse to Poincaré's picture. A newer fission theory of rotating liquid drops has been proposed to study these problems (Chandrasekhar, 1969). Experimentally, the dynamics of rotating liquid drops simulate the characteristics of binary stars and rotating stars.

In nuclear physics, mechanics of fission process is the area which draws a great attention among the researchers. A model of an incompressible rotating liquid drop simulates the dynamic evolution of the stability of the mechanics of nuclear fission process (Cohen, et al., 1974).

In meteorology, dynamic of the breakup of water droplet is closely related to the warm cloud processes. The Skylab demonstration of rotating droplet is also of particular interest in large precipitation drop breakup.

Figure 3 shows some selected frames of the sequences of rotating drops exhibiting "dog bone" or "dumb bell" shape. To get the drop of water to rotate in the "dog bone" or "dumb bell" shape the astronaut conceived a simple technique which he used to produce initially a prolate spheroid by asymmetric excitation of the outer surface of the drop of water. After a few applications of this asymmetric excitation force the drop is caused to rotate at a higher rotational speed which produced an unstable oscillation

mode and the drop then tears into two separate drops. Picture number 1 shows the drop of water rotating in the "dog bone" shape. Picture number 2 shows a drop being initially touched with the rotation tool. The astronaut touches the drop and later he causes it to begin to rotate. Each time the astronaut touched the drop at its outer surface with a rotating motion he caused it to rotate at a slightly higher rotational rate. After a number of encounters with the drop, it was then allowed to rotate until it began to breakup by itself. Picture number 136 shows the drop still in contact with the tool and being excited - note the start of the prolate spheroid shape now occurring. Picture number 165 shows the drop now free of the tool but in a rotating/oscillating mode. Pictures number 747 thru number 752 show how the drop began to reach the unstable mode as it begins to rotate faster until it begins to neck down and breakup into two distinct drops. In future space flights, a demonstration should be performed in the low gravity environment to illustrate the case of the oblate spheroid rotating at increasing angular velocity until a ring of fluid similar to a "donut" is produced.



(Figure 3 to be Continued)

(Figure 3 Continued)

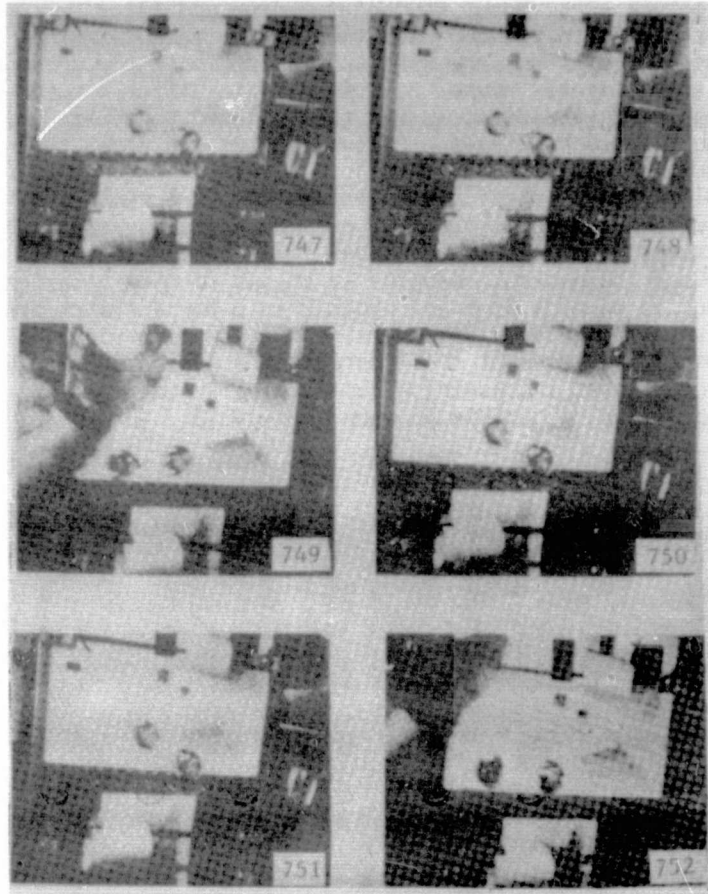


Figure 3. Skylab Fluid Mechanics Demonstration - Rotation of Water Droplet.

Based on the original work by Plateau (1866), Chandrasekhar (1965) extends the work and investigated various modes of oscillation on the stability of rotating drops. For an axisymmetrical form and uniform density, the figure of equilibrium depends on the value of the non-dimensional parameter ξ (Chandrasekhar, 1965)

$$\xi = \frac{1}{8\alpha} \rho \Omega^2 a^3 \quad (4)$$

where Ω denotes the angular velocity of rotation; a , the equatorial radius of the distorted drop; ρ , density of drop; and α ,

the surface tension. As ξ decreases the figure tends to the oblate spheroid, and degenerates into a sphere as $\xi = 0$. However, as ξ increases, the figure rapidly departs from the spheroidal form. The polar regions are flat as $\xi = 1$; as ξ increases beyond 1, the drop develops a dimple; and finally the breakup occurs.

The theory of time dependent evolution of rotating stability of liquid droplets has been a very active research field for many years. It is because of a conspicuous lack of experimental evidence to backup the boundary conditions assumed in numerical computation which makes the computer simulation still not completely explored. In this respect, the Skylab demonstration of a rotating droplet has enhanced the understanding of rotational stability of liquids.

C. Collision and Coalescence of Water Droplets - Recently studies of the dynamics of the collision and coalescence of water droplets has been widely used in simulating the mechanism of nuclear collision and nuclear fusion. These dynamic studies are considered to be a significant step in understanding fusion process of nuclear physics (Cohen, et al., 1974).

In cloud physics, the precipitation process is solely dependent on growth of droplets and ice crystals which is governed by the following three stages: (1) growth by nucleation process, this process includes condensation, ice deposition, and freezing of water droplets and ice crystals on the surface of foreign substances or of the same substances as nuclei; (2) growth by diffusion process, after a droplet or ice crystal has been nucleated and has surpassed the free energy barrier or critical radius, it enters a stage of growth by diffusion; and (3) growth by collision and coalescence process, the growth by diffusion process is negligible compared with that by coalescence process as the size of droplets is greater than 40 microns (μ) radius (Byers, 1965). This implies that the collision and coalescence process is one of the key processes of rain formation.

Figure 4 shows some selected frames of the collision and coalescence of two water drops. Picture number 1 shows the dark colored droplet moving toward the stationary pink colored droplet. The volumes of the two droplets are the same, 30 cm^3 , or a sphere with a 3.85 cm diameter. Picture number 5 is at the moment when the two colliding droplets reached the critical separation distance, and suddenly the distance between two colliding droplets was bridged and coalescence then proceeded rapidly. Pictures number 7, 14, 19 and 20 show how two of the coalescence droplets fused into one, and how the nonlinear wave-wave interaction oscillated in the longitudinal direction. Pictures number 26 and 31 show how the nonlinear wave-wave interaction oscillated in the transverse direction. Pictures number 39, 51, 59 and 72 show the continuous nonlinear oscillations and how the nonlinear damping effect overcomes the nonlinear growth rate. Pictures number 93, 132 and 151 show the typical small amplitude oscillations of a water droplet.

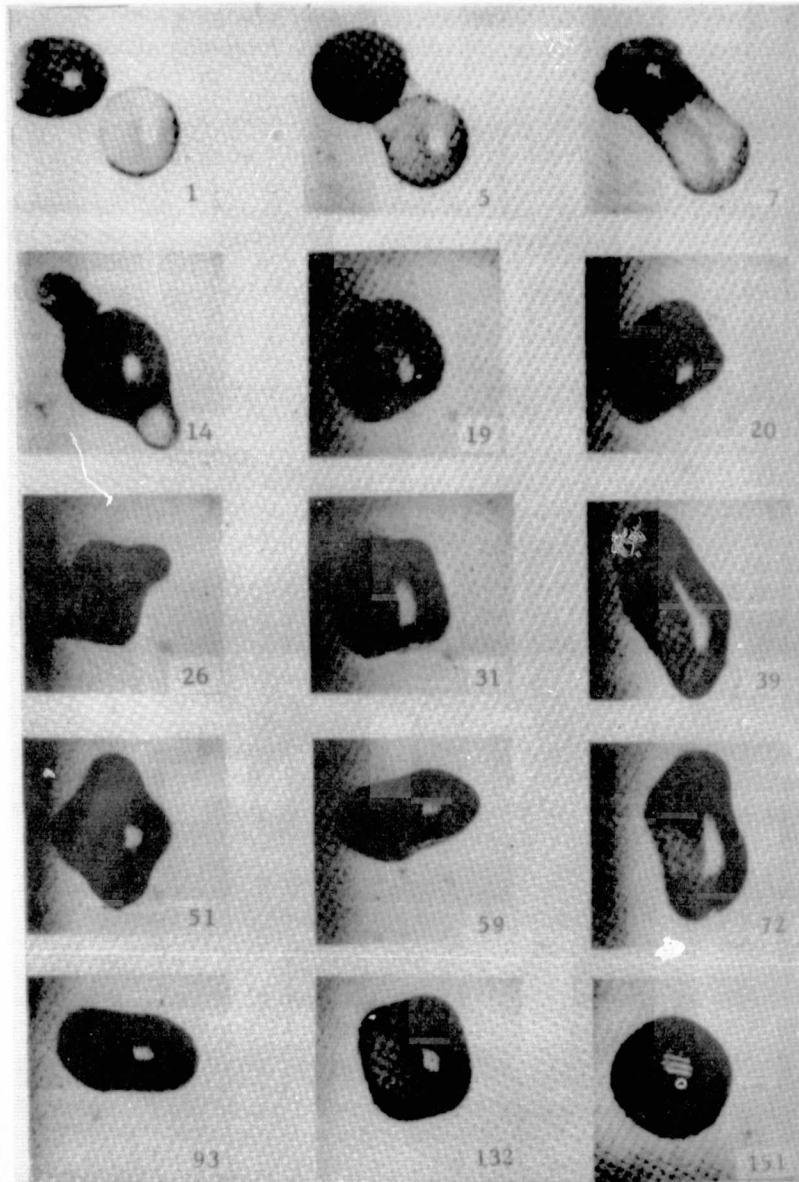


Figure 4. Skylab Fluid Mechanics Demonstration - Collision and Coalescence of Water Droplets.

The basic numerical techniques for studying collision and coalescence of an incompressible viscous fluid are those of the Marker-and-Cell (MAC) method which were developed by the Los

Alamos group (Harlow and Welch, 1965). The MAC method solves the finite difference form of Navier-Stokes equations with the velocity components and pressure defined over a staggered Eulerian mesh. The surface tension effects given by Young-Laplace relation serves as the boundary condition for the free surface. To apply boundary conditions at the edges of the collision (contact point of droplets), further experimental evidence must be obtained to justify either the condition of zero tangential stress or free-slip condition and/or other conditions to confirm the validity of numerical computations. In this sense, Skylab demonstrations of the collision and coalescence of water droplets has helped in our understanding of this phenomena.

IV DISCUSSIONS AND CONCLUSIONS

The study of droplet dynamics has been, for many years, one of the most interesting topics in the fields of atmospheric microphysics, nuclear physics, astrophysics, fluid mechanics, mechanical engineering, and chemical engineering. The Fluid Mechanics Demonstrations (TV 107 Series) performed during the Skylab missions produced excellent photographic data showing the oscillation, rotation, collision and coalescence of water droplets which simulate various physical models of interests under low gravity environment. Also, these TV 107 series of films provide interesting observations and illustrate the potential beneficial use of the low gravity environment for various branches of research. Particularly, scientific and technical evaluations have been provided by Skylab demonstrations to support the Zero-Gravity Atmospheric Cloud Physics Laboratory project in the future missions of Spacelab/Space Shuttle.

During the Skylab missions, special equipment was not available and video recording was used for data collection. These video tapes were subsequently transferred to 16 mm movie film which was then supplied to the researchers for analysis. In this respect, because of the restriction of speed of video recording, a laboratory type controlled experiment was not performed in the Skylab missions. However, qualitative in nature, these films have provided much interesting information and illustrate the potential of an orbiting research laboratory to provide data beneficial to terrestrial research problems.

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