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Date June 10, 1987

Fluid Streamlines Flow in an Annular Cavity

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Charles Stephen Sanford

August 1987

ACKNOWLEDGEMENT

"Separation on Axisymmetric Bodies, Including Flow Visualization" was the topic of study at the von Karman Institute for Fluid Dynamics (VKI) at Rhode-St.-Genese, Belgium. This North Atlantic Treaty Organization (NATO/AGARD) supported institute generously allowed their research facilities to be used from 21 June to 16 July, 1982. It is hoped that this thesis will contribute to the continued cooperation of the University of Tennessee Space Institute (UTSI) and VKI under the aegis of NATO (AGARD).

Professor J. Sandford was the supervising instructor and special thanks go to him and my colleague, John Pattison, of Imperial College (Kings College) in London, England. I am most appreciative of the personal efforts given by Deans Goethert and Mason of UTSI for their letter of introduction. I am also appreciative of Congressman Bill Boner's staff in expediting my passport application.

Additional appreciation is to be given to Dean Goethert, Connley Powell, Jerry Westbrook, Ted Paludan and Ralph Kimberlin; all of whom have shown understanding, instilled confidence, and given suppport in my educational pursuits. There is no expression that I can give that can adequately express my feelings. I know that the knowledge that they have given to me will be shared with others.

ABSTRACT

The phenomenon of study is "Fluid Streamlines Flow in an Annular Cavity".

Previously prepared photo-images are available from independent research conducted with J. Pattison of Kings College (London, England) for Professor J. Sandford (retired) at von Karman Institute of Fluid Dynamics (Brussels, Belgium) during the summer of 1982.

Dye-injected water is mapped onto a series of Euclidean planes within the annular cavity of a blunt, ogive axisymmetric body which has a variable angle of attack, constant fluid flow, and a 1:1 ratio of cavity depth to width.

This paper shows the relationship between digitized flow-field images, the geometry of their location and associated mathematical models which are used to derive computer codes.

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INTRODUCTION

The purpose of this paper will be to show the results of an experiment in inter-continental research. The experiment's hypothesis is to be differentiated from this paper's thesis. The results relate not only to the experiment, but also to the study methodology, the research environment, the equipment and materials used, access to laboratories, and administrative cooperation.

The reason for the UTSI and VKI exchange program is to maintain a cooperative scientific spirit between the research institutes. In addition, the visiting staff and scholars can share ideas and innovative concepts which are mutually beneficial.

The purpose of the experiment under discussion is to describe the fluid flow in an annular cavity of an ogive, axisymmetric body. Refer* to Appendix A, Figure 1. The primary laboratory objective of the flow visualization study was to measure the oscillation period of the vortex trailing from the body's cavity as a function of angle-of-attack and to devise a method to record the data.

*All Figures are in Appendix A, attached.

I. HISTORICAL TECHNIQUES

Flow visualization is a concept that can range the gamut from watching waterdrops splashing on a flat surface to telemetrying binary information from a distant galaxy for computerized data display. Some of the techniques are highly specialized and imbedded in protected computer codes while other techniques are self-evident, even to the casual observer. Standardization of techniques for a developing research science is an ongoing process. There are times when it is expedient to adapt procedures from a related field or sub-discipline of study in order for research and discovery to be managed in an orderly fashion. This is not to make light of the serendipitous discovery, but it is to emphasize that creative work can be enhanced by a managed engineering program. This section presents some of the historical procedures that have been used for describing fluid streamline flow.

Maskell (1981) postulated that for a blunt body, the lines of separation determined by the envelope of converging streamlines inside the viscous layer interacted with inviscid 3-D streamlines; hence, computations could be facilitated to predict drag involving free vortices resulting from flow separation.

Tobak and Peake (1982) state that "3-D separation flow represents a domain of fluid mechanics of great practical interest that is . . . beyond the reach of definitive theoretical analysis or numerical computation".

For flow visualization, Legendre (1956) used streamlines adjacent to the surface with trajectories based on a series of singular and continuous vector fields; Lighthill (1963) used skin friction line patterns from saddle points of bifurcation; Hunt (1978) utilized planes of symmetry; Smith (1969) used conical flow. Others - Perry and Fairlie (1974), Legendre (1965, 1972, 1977), Oswatitsch (1980), and Tobak and Peake (1979 and 1980) - followed Poincaire's (1928) "On the Curves Defined by Differential Equations" Poincaire's formulation was based on the concept of stream tube flow where the inflexional boundary-layer profile developed on cross-flow planes and the maximum velocity was induced by the largest vortex structure. Andronov's (1971 and 1973) "Bifurcation Theory" nutured the ideas of Sattinger (1980), Joseph (1976), and Benjamin (1978).

In 1980 at Arnold Engineering and Development Center (AEDC) Maegley and Carroll (1982) measured the heat related to a missile's annular cavity. They found that as the annular cavity increased in length down the axis, the heat transfer coefficient increased downstream, an axial slot had a higher heating rate than did the missile surface, and the cavity opening caused flow separation over the forward section of the nose.

Bozeman and Dalton's (1973) study stated that most of the strength of the vortex is concentrated in the upper portion of the cavity and that there is a pair of counter-rotating vortices of much smaller strength located in the lower corners of the cavity. They also stated that, as the Reynolds number increased, the vortex center moved toward the center of the cavity (ie., away from the boundary shear layer). Their vorticity was the transport form of the Navier-Stokes equation (ie., vorticity as a function of the stream function).

Sarohia's (1977) concept was that an open cavity was shallow when the propogating disturbance was amplified through the shear layer and that the cavity was deep when there was a fundamental acoustic depth mode acting as a resonator with the shear layer providing a forcing mechanism. He categorized cavity size as open or closed. A "closed" cavity allows re-attachment of the shear layer in the cavity bottom, ahead of the downstream wall. An "open" cavity has a width per depth (b/d) ratio of about 7.5 and separation occurs upstream and re-attaches downstream. He used dimensionless analysis for determining the frequency.

Lester Lees (1964) states in his article on solar plasma and the geomagnetic cavity that, "the solar plasma wind and the geomagnetic cavity is analogous to the supersonic continuum flow over a blunt-nosed body."

Roshko's (1955) comments on a rectangular cut-out were, "The formation of the vortex occurs by the deflection of part of the separated boundary layer into the cavity . . . . The intermittencies that are observed to occur and which may create strong pressure and velocity variations, appear to be due to switching back and forth between two possible stable states."

Benjamin and Denny (1979) gave the convergence of a numerical solution for 2-D flow in a cavity.

Pan and Aerivos (1967) described steady flow in a rectangular or square cavity with a bi-harmonic equation including polar coordinates in the square corner.

White (1974) gave the equations of motion of incompressible Newtonian fluids in cylindrical coordinates. He suggested that "it is generally useful in fluid mechanics (1) to choose the most convenient origin of coordinates, with luck making the flow appear steady, and (2) to study only the velocity field as a function of position and time, not trying to follow any specific particle paths".

As per Shunk (1971),

> "The streamline pattern shows a region of strong inflow near the surface with a deep region of weaker outflow aloft. In addition, the distribution of streamlines show strong vertical motion over the major portions of the region. The vertical component of the motion field appears weakest near

the lower boundary and away from the axis . . . . Because of their importance as elements in all of the equations used in this study, the radial and vertical shear of the tangential, vertical, and radial velocities have been analyzed . . . . A most interesting feature of all of the velocity shear fields is the presence of a center of intense velocity shear near the lower boundary and near the axis . . . . The acceleration of the three velocities and the acceleration of the vorticity . . . reveals some of the same features of the velocity shear fields, i.e., the presence of centers of very large accelerations (positive and negative) near the lower boundary and axis."

A study by Sinclair (1966) said,

"the air is spiraling . . . downward and slowly outward into the rapidly rising sheath of air surrounding the core . . . the Rankine combined vortex is probably the simplist vortex model that simulates, to some degree, the tangential motion of both natural and laboratory vortices . . . . Many vortex models have been proposed mainly by research meterologists and fluid dynamicists, yet only a few exhibit the characteristic downward motion within the core . . . reference to Gutman's (1957) model based on Boussinesq equations of the large vertical accelerations . . . . The model is a stationary, steady state, axially symmetric system . . . . It is significant that the tangential velocity profile indicates solid rotation v/r is constant for the inner region . . . and irrotational motion v*r is constant for the outer region . . . ref. the Donaldson-Sullivan vortex , "The model is based on the Navier-Stokes equations for an incompressible fluid in steady state flow where the radial, tangential, and axial velocities are in cylindrical coordinates . . . ."

Vortex (ie., spiral or helical flow) is currently studied by astro-physicists. As per Smith (1973): "If the particle has some speed along a . . . field line, it will follow a spiral or helical trajectory. When the particle moves into a region of higher field strength, the circular orbit shrinks while the circular speed increases. Since the particle's total kinetic energy cannot change, its motion along the field line must slow down; eventually the forward motion will reverse at the mirror point".

Another flow-field study technique is via mass-balance-equations. The standard technique used by Bear (1979) for a water balance is to measure flow rate at the center of a rectangular grid rather than at the nodes of a grid cell. Bear used a square aquifier with three impervious sides and the fourth side draining. He stated, "We see here the similarity between writing a water balance for a cell and the numerical approximation of the partial differential equation, except that the balance equation is derived on the basis of physical (rather than mathematical) considerations only".

In water tunnel experiments a digitization technique must quantify various imprecise groups of flow elements with "fuzzy" boundaries. A maximum and minimum density range must be prescribed for image recognition and group assignment. This range can be specified by turbidity. Turbidity is a measure of the light-transmitting properties of water. Impurities of collodial matter (ie., injected dye) will scatter or absorb light and thus prevent its transmission. The measurement scale ranges from 0 at a minimum to 1.0 at a maximum. The old standard (American Public Health Association, 1946) was a candle flame image obscuration due to silica (diatomaceous or fuller's earth) in distilled water. Newer techniques allow density slicing of gray levels and false color assignments with reproduction on computer monitors and inked printers and x-y plotters.

Refer to Appendix C for a source list of recent works in this field.

II. EXPERIMENT

EQUIPMENT

Refer to Figures 1 and 2. The series of VKI experiments were performed at the VKI water tunnel (WT-1) at various flow rates which corresponded to a Reynolds number of approximately 104,000 per meter. The test model was a brass cylinder with an ogive nose, and it had an annular cavity with a depth to width ratio of unity; see "d" and "b" equal to 10.15mm in the figure. Dye injection ports were located on the nose, within the cavity, and upstream of the body for free stream-line markers. Notice the ports numbered from 1 to 13 in the figure. All unused dye supply lines were plugged so that fluid did not flow through them to alter the cavity flow conditions.

The flow phenomena were recorded using a 35mm Nikon F still camera, Sun Zoom lens, fluorescent back lighting, 3.5 kw indirect incandescent spotlight, with Kodacolor film ASA 100 at F5.6 and ASA 400 at F16 and a shutter speed of 1/125 second. There were 122 photographs developed from rolls #36356, 36456, 36457, and 55268. Examples are given in pictures labeled as Figure 3. Notice the depth of field for background images.

A short video film of the flow phenomenon was made using Sony VCR (Betamax) equipment. It consisted of camera DXC-1610P and 17-102mm variable zoom lens (1.2.1). See Figure 4.

The flow patterns were studied for different angles of attack (alpha) with dye-holes rotated to different angular positions (phi) about the plane of symmetry.

Alpha (in degrees) was 0, 2.5, 5.0, 7.5, 10, 15, and 20. Phi (in degrees) was 0, 45, 90, 135, and 180. Refer to Figure 5 for alpha and phi as related to the annular cavity. Refer to Figure 2 for the dye-holes' location. Each combination of these angles was photographed at various flow rates ranging from 11.01 to 13.95 kilo-liters per hour (kL/hr). The photograph in Figure 6 (top) shows the following information: 14.0 kL/hr. Dye injection information is best seen from Figure 6 (middle) as follows: port 9 initiated the purple streamline shown as the cavity's inner vortex, port 7 was the origin of the cavity's outer vortex shown as green streamlines, and the red line was the free stream maker originating from the source and flowing from top to bottom. Notice that in Figure 6 (bottom) the free stream velocity was reduced to 12.3 kL/hr and the image shows no outer vortex within the cavity.

UTSI laboratory equipment photo-digitized the flow visualization images given in Figure 6 for personal computer data base usage. These images were supplied in the form shown in Figure 7 and are of unsuitable quality for computer analysis.

METHODOLOGY

Various modern three-dimensional projective views utilize variations on isarithmic mapping which describes the intersection of a statistical surface with a horizontal plane (more generally stated, the intersection of a statistical volume with a datum plane). The difference in the meaning is to expand a flat and horizontal mono-grid of numbers into a potentially curved-body configuration with possibly varying states of stratified and dynamic parameters.

The terms "grid," "control point," and "control volume" are often used without full description.

Consider a two-dimensional grid as any i-j matrix or lattice structure which is delineated by lines of minimal thickness. At the intersection of two of these lines a measuring probe can theoretically determine the numerical value of a parameter. Logic dictates that a finite volume's function cannot describe a dimensionless position. Since a point is dimensionless and a probe has a definite size and volume, then there can be no "real" measurement.

"Grid point" or "mesh point" is usually reserved for a theoretical position which is the intersection of two lines. These lines are intersections of two surfaces and are generally used for a matrix collection of points. A "control point" is a standard reference position that correlates all other points in terms of itself. This correlation includes position, at a minimum, and can be expanded to include the statistical volume database of dynamic parameters collected for the matrix of points. "Control point" could be replaced by the phrase "control volume", since error can be associated with the control point's probable position as measured with a probe of a specified size and accuracy. "Control volume" is reserved for the domain of classical thermodynamics where an idealized volume is maintained in order to measure mass flow conditions. Similarily, "control mass" is used to monitor a constant quantity of matter, regardless of its density, volume or position.

Another technique often employed in the manipulation of a database is to describe the position of a two-dimensional central datum value relative to its adjacent North, East, South and West (or left, right, up, and down) mesh points. This is a typical five-point star arrangement. This technique can include a circular co-ordinate system with the central value located at the intersection of a radial line and a circular line. This can be enhanced by using sub-divisions of a smaller scale with a greater accuracy. A particular grid can have its linear dimension halved (and halved again) between any two points, thus resulting in that many more cells containing flow information. Obviously, the size of the grid is limited by equipment accuracy.

Classical thermodynamic control volume and control mass elements with recognized ensembles of particles were utilized in this study. Our model's geometric body and cavity shape set the boundaries on which the fluid flow interacted. The nose attitude relative to the flow direction established the plane-of-symmetry. A marked control mass was established within the annular cavity. Conceptualized control volume grid boundaries within the cavity allow analysis of the marked control mass which was observed within the flow regime of interest. Image recognition of an instantaneously measured (near real time) steady-state flow condition enumerates the presence or absence of the control mass within each incremental control volume elements. Remote sensing techniques of dye line observation of fluid flow streamlines on the flow tube successfully accomplished a mapping of the dye injected water in the annular cavity. Further data manipulation included computer photo-digitization as presented in Figure 7.

Theoretical mathematical treatment of fluid flow is exemplified by descriptive formulation of an "equation of state" which presents a frame-of-reference and describes a phenomena's existence and behavior by its sets of coordinates. The equation of state consists of two three-dimensional spaces:

position space and momentum space. There is an implicit notion of causality (Segal, 1976) where a three-dimensional position possesses time sequencing so that there is a "future" direction at each point (time does not flow backwards). A 4-D manifold describes a 3-D position with temporal order. The six-dimensional phase space can be determined by defining a group of particles' wave front in terms of its position and momentum vector. At an observed moment in time these particles have a quantifiable position, mass and speed (energy), and direction. This observed mass density is inside a finite volume element and can be described as a statistical distribution function for particles of a given species.

One of the problems of a descriptive statistical database is associated with the selection of an origin. For example, the "regular" three-dimensional Cartesian co-ordinate system has positive x, y, and z axes. Obviously, this positive quadrant (actually, an "octarant") has negative quadrants associated with it in the minus directions as measured from the origin. Mathematical manipulation of these negative regions could yield a "complex" solution which results in an "imaginary" component (i); where the square root of a negative number is contained in the solution to the equation. According to Phillips (1963), "It is desirable to be able to say that every quadratic equation has two roots, every cubic equation has three roots . . . ." A search of the literature (Markushevich, 1962) shows that the Dutch scholar Mercator (ca. 1560) constructed conformal mapping using a transformation involving "i". Only the positive, real number system is conceptualized for flow visualization.

The flux of particles in a control volume can be described as having a particular momentum with a corresponding set of equations of motion. For any given set of initial conditions the actual measured data consists of time, free stream conditions, body configuration, grid location, control mass particle density, and speed and direction of the particles' travel.

An error analysis used in conjunction with a mathematical model of the equations of motion should show a more accurate fit of the calculated data to the actual data when the coefficients are sufficiently accurate.

The control mass of particles had no net flux change because it was a marked incompressible fluid in steady-state flow conditions. It did have position and velocity changes as observed in real time test conditions and as shown in Figures 3 and 6.

III. DISCUSSION

TEST RESULTS

Refer to Figure 8 for designated areas of the cavity region where "A" is the annular cavity inner vortex streamlines, "B" is the cavity exit's trailing streamline area, and "C" is the cavity exit area at the initial interface between the exiting streamline with the free-stream. At an angle-of-attack of zero, the dye lines from the model's nose were oscillating at the leading and trailing edge of the annular cavity. The motion at the leading edge indicated that the streamlines were oscillating at the junction of flow into the cavity and/or going past it, thus implying a point of possible bifurcation due to a standing wave at a hydraulic jump. The oscillation amplitude at the upstream cavity opening was of the same general order of "magnitude" and frequency as the downstream oscillations. In this instance "magnitude" refers to the distance from the peak amplitude of the exited streamline from the body surface towards the freestream. The periodic amplitude which increased at the downstream cavity opening was seen to have an amplitude that was greater than the leading edge amplitude, and which was damped with time of motion (ie., directly proportional to the length of time adjacent to the body). See Figure 9 for the test results' data-plot of the Cavity Oscillations for areas A, B, and C. These test observations show increasing frequency of oscillations (ie., decreasing time per oscillation) for area "B" plotted as a function of increasing fluid flow rate (kiloliters per hour). There was insufficient data gathered to make a determination for regions "A" or "C". However, all measured oscillations varied between 2 and 6 every ten seconds.

Under these same general flow conditions another interesting phenomena was observed for small angles-of-attack (ie., approximately 7.5 degrees). When the dyed control mass was released into the body cavity it settled into a pool, then welled up and flowed towards the downstream edge of the cavity. At this edge, the dye stream bifurcated. One of the new streams flowed along the surface of the model and the other became a primary, inner annular vortex having originated near the down-stream plane of symmetry which then travelled 180 degrees around the annulus to the upstream plane-of-symmetry. This upstream plane-of-symmetry is where the free stream entered the cavity and "forced" the inner annular vortex to reverse direction. Upon reversing directions (apparently due to the large cross-flow components of the free stream velocity) this new, outer, counter-rotating vortex concentrically encompassed the inner vortex and travelled back within the annular cavity to the downstream cavity opening where it periodically exited the cavity into the free-stream interface at the boundary layer. Refer to the green streamline in Figure 3 (bottom).

During the initial visualization period it was hypothesized that there was fluid flow within the annulus and there were stagnation areas in the corners. This is shown to be the case by visual inspection of Figures 3 through 8. Changes to the angle-of-attack (alpha) and freestream velocity altered the flow field around the body and within the exposed cavity. Note the variations in Figure 6's streamlines, flow velocity and alpha. The visual results confirm the hypothesis. Furthermore, increasing the freestream velocity, at a constant angle-of-attack, increased the frequency of oscillations of the cavity's exited streamlines (i.e., a decrease in the time per oscillation). Refer again to Figure 9 (area B).

Quantification of results is based on relative flow rates since calibration curves for the Rotameter pressure-head tank drain valves were not standardized. The manual count of oscillations per unit time had an error of reproducibility based on triggering a stopwatch on verbal command (plus/minus 0.1 second). Other errors were suspected for intermediate and large angles-of-attack (eg., 15 degrees) where the test cell's wall clearance between the model's body surface decreased and allowed side wall interference with the free-stream velocity.

DATA PROCESSING

Digitization is a mapping procedure that can be automated by video-camera capture of the images (refer to Figure 4 for a photograph of a video image made during this research work at VKI).

Photographs of the dye injected streamlines were digitized so that the size and spacing of the fluid streamlines could enable a numerical description to be applied to the vortex flow field pattern. The digitized images were inadequate due to the lack of clarity as shown by contrasting Figures 6 and 7. The resolution of the digitized images is much coarser than the photographs themselves. Inspection of the bottom perimeter of the images in Figure 7 show extraneous data points. These "points" appear as small rectangles (pixels), rather than discrete points. There is also a similar alignment error observed on the left perimeter. This can be due to the digitizing camera and software, the intermediary personal computer to which the data was transferred, or the printer on which the images were printed. No information was supplied by the cooperating laboratories which would enable a determination as to specific equipment or operator procedure which could be improved. One can only surmise that any combination of the following occurred:

a) the max/min values of black/white for the digitizing camera were not calibrated on the darkest and lightest areas of the photos,

b) the calibration areas of the three photos were inconsistent,

c) the Vax mainframe computer to IBM personal computer (PC) data-transfer lost or compromised the original digitized data,

d) the PC software/hardware was not "bit" compatible with the transfered data (ASCII, USASCII, etc.),

e) the printer's dot matrix pin head was misaligned either physically or electronically.

Computer processing was to compare the actual flow data of size, particle density, location, and wavefront travel time to the results from numerical code generations of a theoretical mathematical model. Specifically, the digitized image profile of the amplitude of the cavity's exiting streamline would have matched an analog algorithm. Graphing the results of repetitive numerical code changes and comparison to the measured data would have shown an error analysis of the generated math model. A multi-variant linear regression (ie., a form of least-squares fit) could have been calculated. An improved math model should have shown a convergent solution that would superimpose its generated data onto that of the measured data when graphed. This would be a one-to-one mapping signifying close agreement between the empircal and theoretical results. A perfect coorelation would be 1.0 coefficient-of-determination.

Sufficiently accurate computer programs can describe similar phenomena by using appropriate scaling variables for coefficients of the mathematical model's equations. Again, please refer to Appendicies B, C and D for current examples of computer software, sources of recent investigations, and mathematical approaches for analysis.

EQUIPMENT

Any equipment has accuracy which is inherent to its intended function and designed operating conditions. Normal wear and usage will cause a trend towards misadjustments, mis-measurements and possible failure of the equipment. Graphical analysis of the flow functions observed at the KVI water tunnel show an error analysis as data points plotted with minimum and maximum ranges. Refer to Figure 8. High-speed video camera time sequencing can enhance the measured time because of its image capture rate of 1500-3000 frames per second. This corresponds to 0.0003-0.0007 seconds per image. Other filming techniques can be even faster, but the associated equipment and film processing costs will increase.

The water velocity was dependent upon the flow rates from the gravity discharge tank into the test chamber. For large bodies there can be sidewall interference. Hence, the accuracy of the measured flow rates were predetermined by the drain control valves. Since this experiment did not standardize these control discharge valves, then no absolute flow rate was determined. However, relative flow changes were recorded and the accuracy was taken to be the reproducible scale readings.

The model body contained interfering air bubbles that attached to the inside of the annular cavity. The lathe machine marks were hypothesized to be the root cause of bubble attachment due to surface roughness allowing a larger surface area to which the bubbles could adhere. A replicated body was manufactured, and vernier marks were scribed, the base solder joints were smoothed out, and recommendations were given for the body to be surface plated.

APPLICATIONS

The analytical techniques have been previously presented by this American educated author in various inter-disciplinary documents, as follows (refer to the List of References for a more complete description):

1. Separation on Axisymmetric Bodies, July 1982.

   The velocity field is a function of position and time; i.e., position and momentum (mass and velocity, where velocity is the change of position with time). Any equation-of-motion or equation-of-state which is developed empirically from actual curve-fitting of data is limited by the variables and constants selected for study.

2. Position: i, August 1982.

   For interstellar navigation, place an artificial grid to determine various positional shifts; ie., radioactive markers in helio-stationary orbit. Computational techniques for theoretical results can be based on Alfvenic solar-wind flow past magnetic and non-magnetic planets.

3. Cartographic Model . . . Solar Wind, December 1982.

Technological advancement in aerospace research of Very Long Base Interferometry (VLBI) has incompatible premises of (a) measuring the Earth's crustal movement with a fixed celestial frame-of-reference and (b) a fixed Earth baseline for measuring the stellar motion. Hypothesis: there is a positive correlation between terrestrial energy levels as measured by crustal plate shifting and compared to solar plasma activity.

4. Realistic Time-Geometry, March 1983.

Chronogeometry (space-time geometry) has dynamic variables of motion affecting a homogeneous isotropic ellipsoid in a uniform field that sets its longest axis parallel to the lines of force. A paramagnetic body moves from a place of weaker to stronger force field and a diamagnetic body moves from a stronger to weaker force field. Alfven waves describe this force field and a body may behave para- or diamagnetic depending on whether it is in a less or more permeable medium than itself.

5. Space Shuttle Proposal, January 1984.

A water tunnel model of the space shuttle with a strong-back mounting mechanism is proposed. A tethered orbiting vehicle can be attached for solar-wind interaction during cruising plane-change maneuvers.

6. UTN Project Report, December 1979.

A large stadium was designed with an air inflated roof with fans for HVAC air flow. An annular cavity with wind induced vortex flow can decrease the horsepower requirements and operation costs for the fan motors.

IV. CONCLUSIONS

Historically, the procedure of flow visualization has not been a precise measuring tool for scientist and engineers. However, at a minimum, it has been a creative approach for analysis which allows the investigator to conceptualize flow-field phenomena. An understanding of the associated flow-field principles can enable the observer to enhance probe placement for more accurate and intensive measurement. This saves time and costs of engineering research, development, test and evaluation.

The primary reason for this sponsored research at VKI was to learn and benefit from the differences between the U.S. graduate study methodology and the continental (European) laboratory procedure. The experimental techniques have been purely European, as per this NATO funded institute's summer study program. Dye-injected water was mapped onto a series of Euclidean planes within the annular cavity of a blunt, ogive, axisymmetric body which had a variable angle of attack, constant fluid flow, and a 1:1 ratio of cavity depth to width.

The experimental hypothesis was that there was fluid flow within the annulus and that there were stagnation areas in the corners. The results confirmed the hypothesis. Furthermore, increasing the freestream velocity, at a constant angle-of-attack, increased the frequency of oscillations of the cavity's exited streamlines. The experiment's hypothesis must be differentiated from the paper's thesis. The results of this study relate not just to the actual experiment, but also to the study methodology, the research environment, the equipment and materials used, access to laboratories, and administrative cooperation.

The purpose of this paper has been to use the phenomenon of study, flow visualization of fluid streamlines, to explore the relationship between digitized flow-field images, the geometry of their location and associated mathematical models which are used to derive computer codes. In fact, this shows how basic research can be developed for applied research needs.

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APPENDICES

Appendix A: FIGURES

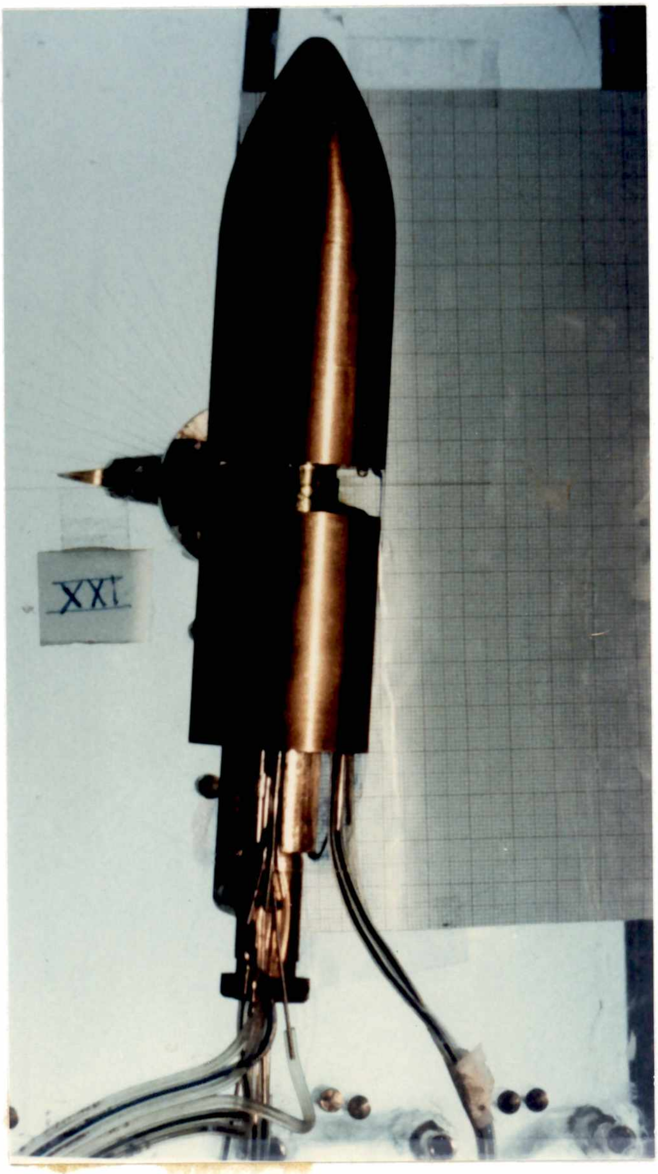


Figure 1. VKI Water Tunnel Test Chamber.

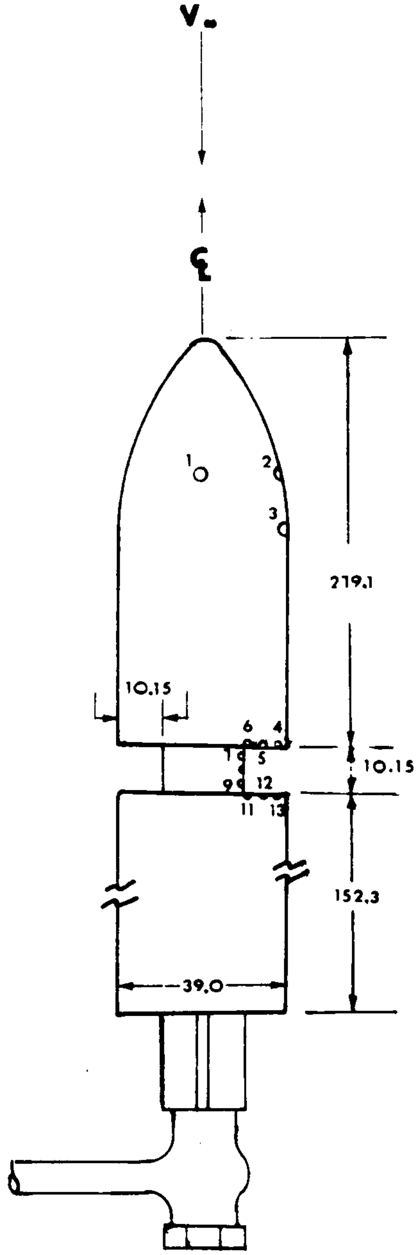
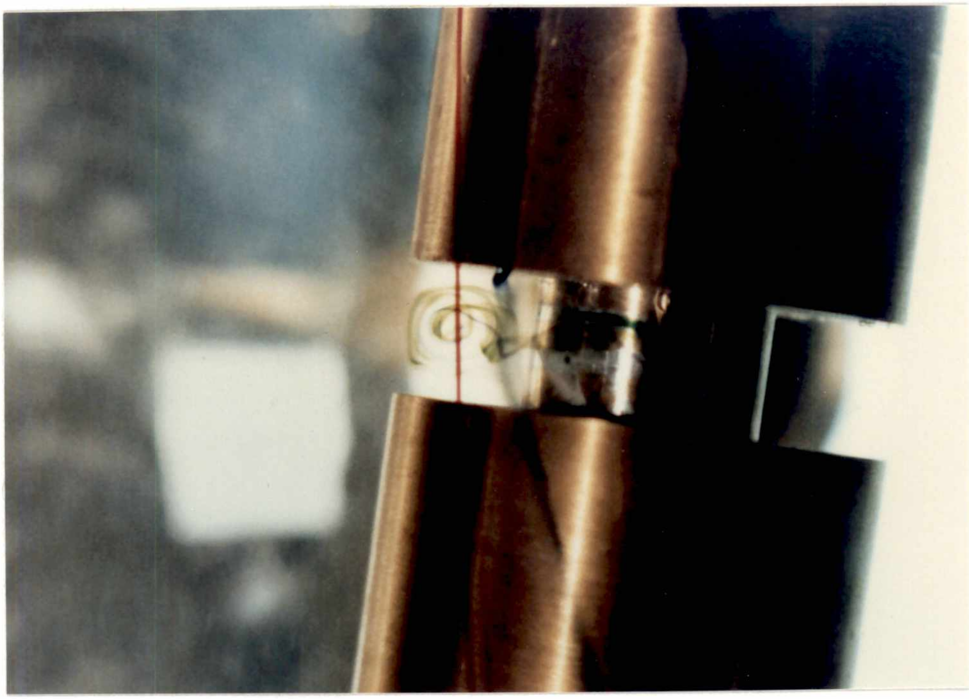


Figure 2. Experiment's Body Configuration (mm).



Top

f5.6

ASA 100

Bottom

f16

ASA 400

Figure 3. Camera f-stop Depth of View

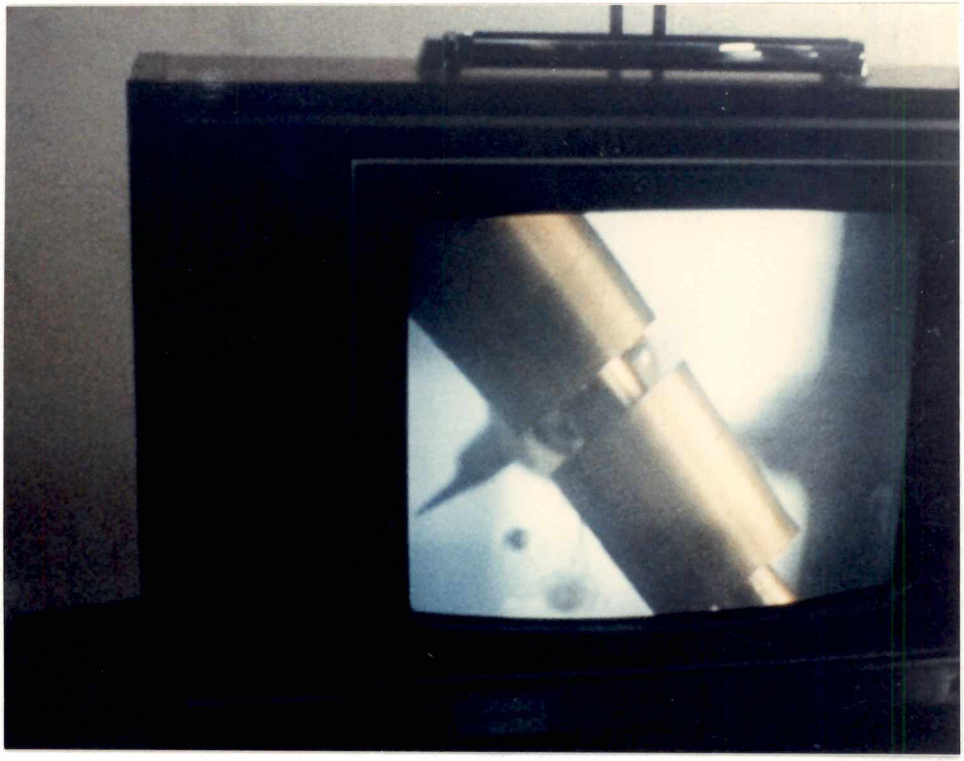


Figure 4. TV Image of VCR Tape.

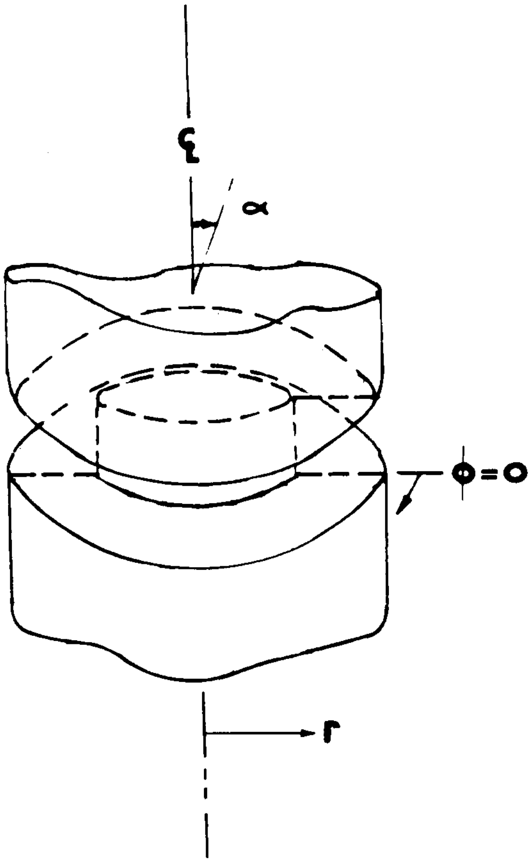
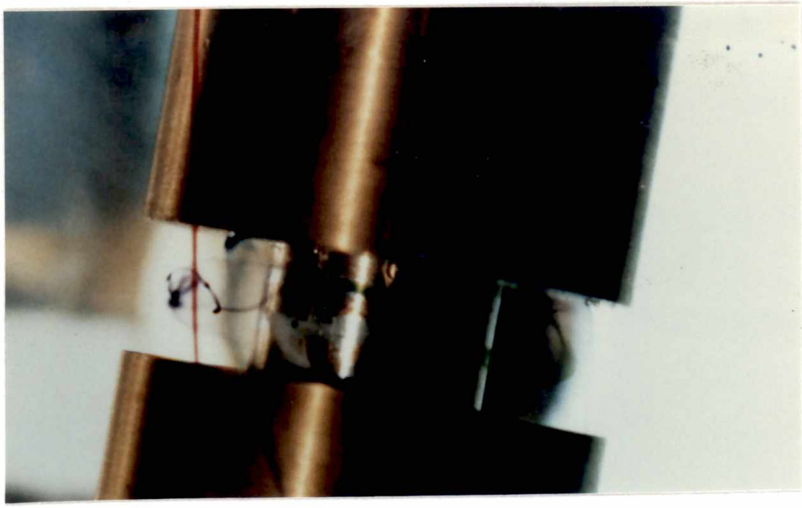
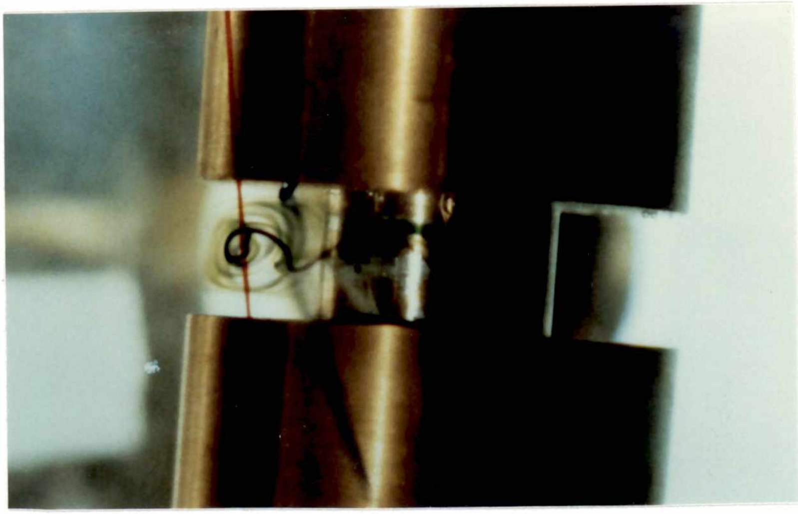


Figure 5. Annular Cavity Frame-of-Reference.



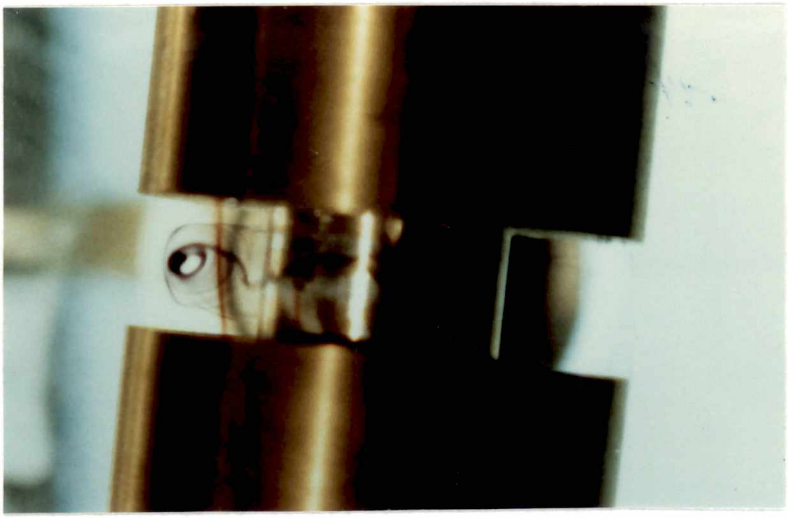
Top

phi=135 degrees
alpha=10 degrees
v=14,000 liters/hour
dye: 2 (purple)
4 (blue)
7 (green)
9 (purple)



Middle

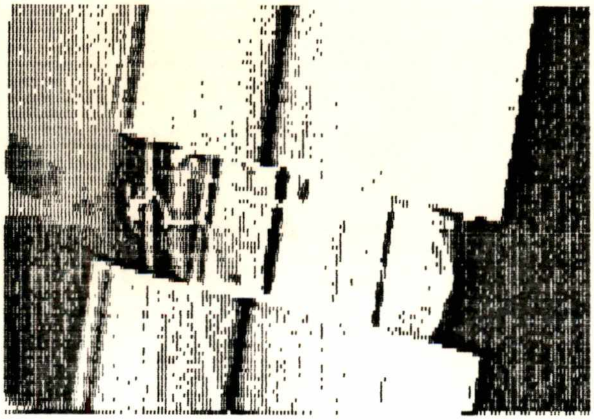
phi=135 degrees
alpha=7.5 degrees
v=14,000 liters/hour
dye: same as above



Bottom

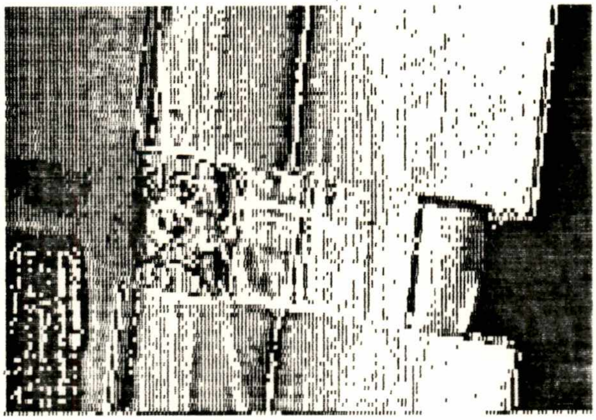
phi=135 degrees
alpha=7.5 degrees
v=12,300 liters/hour
dye: same as above

Figure 6. Annular Cavity Streamlines.



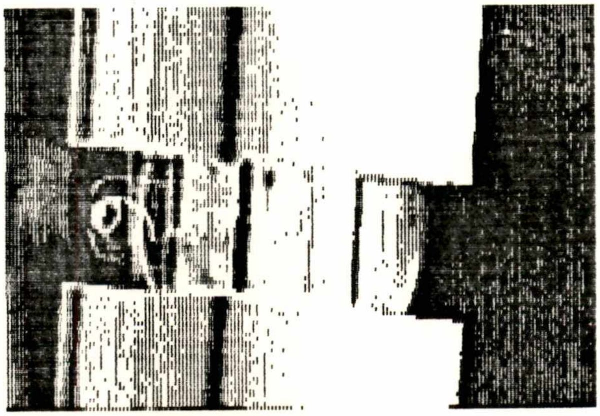
Top

phi=135 degrees
alpha=10 degrees
v=14,000 liters/hour
dye: 2 N/A
4 N/A
7 N/A
9 N/A



Middle

phi=135 degrees
alpha=7.5 degrees
v=14,000 liters/hour
dye: same as above



Bottom

phi=135 degrees
alpha=7.5 degrees
v=12,300 liters/hour
dye: same as above

Figure 7. Photo-digitized Images.
Photo-digitization of Figure 6 (preceeding page).

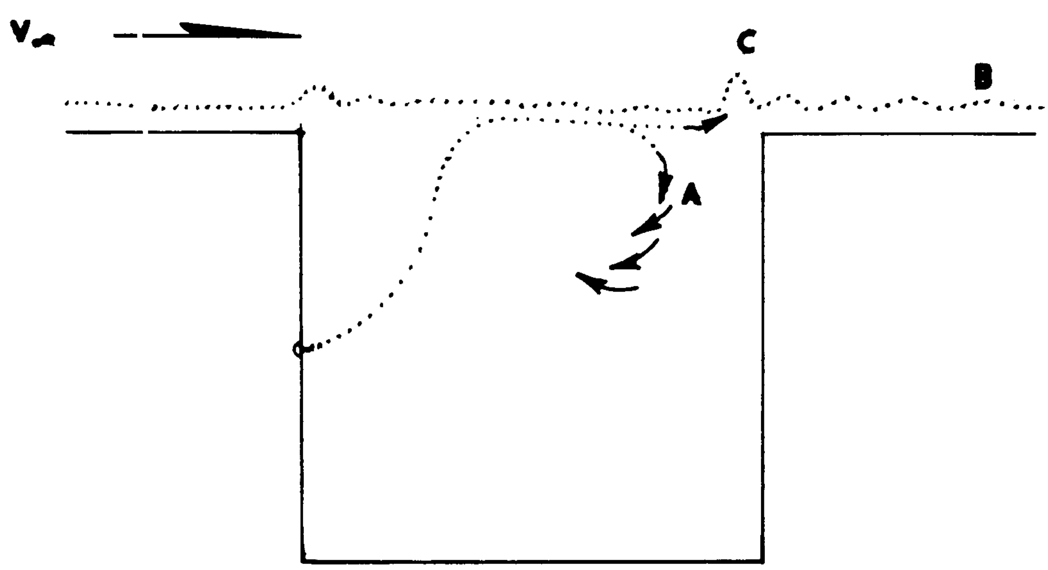


Figure 8. Cross-section of Annular Cavity Flow Regimes.

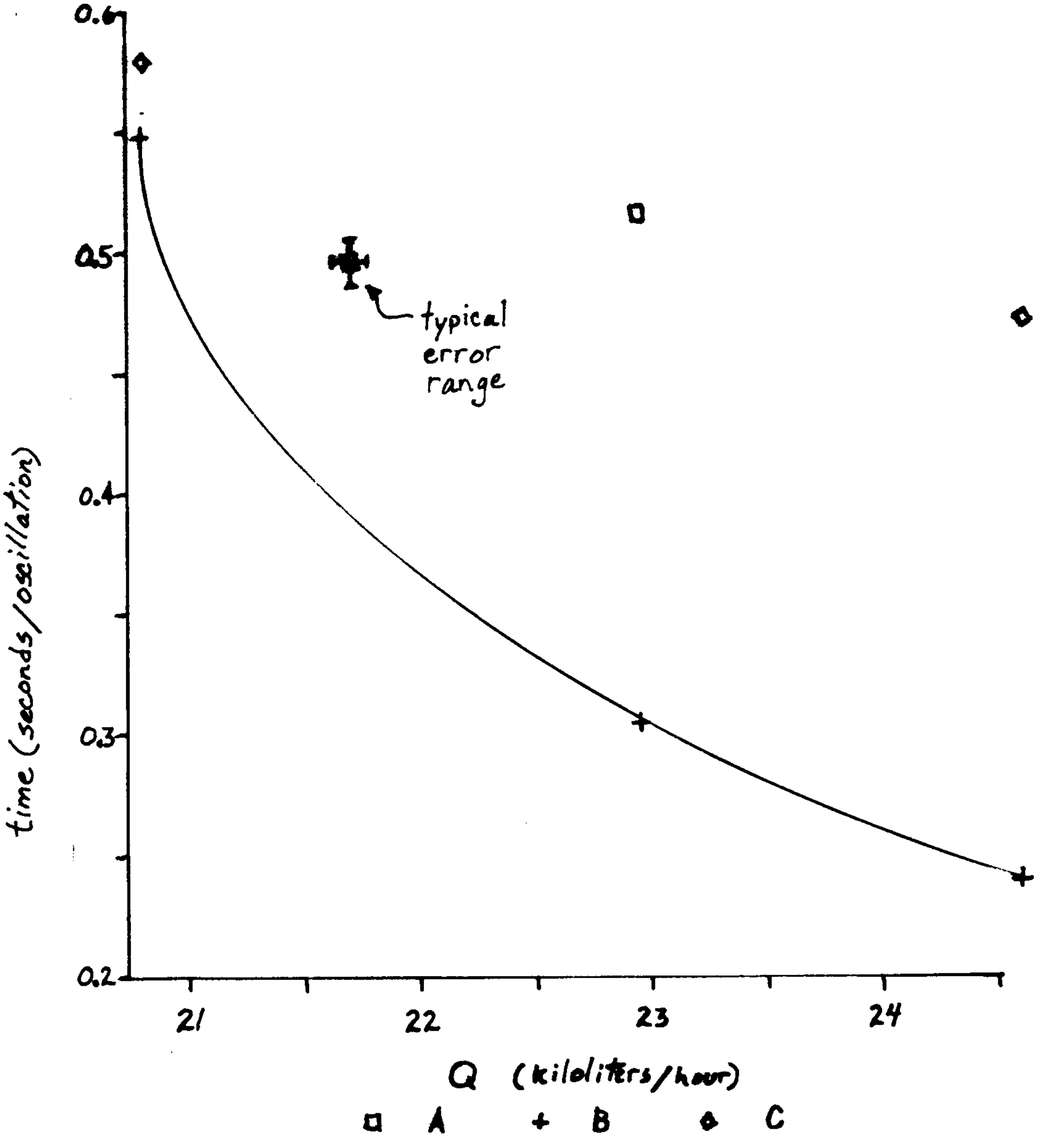


Figure 9. Cavity Oscillations.

A, B and C refer to Locations on Figure 8.

Appendix B: COMPUTER SOFTWARE

COMPUTER SOFTWARE

The following list is derived from the COSMIC computer database, see the List of References. Also, "Appendix C: Sources" contains references to recently developed micro-computer software codes.

LAR-11877: Digital Computer Program for Generating Contour Plots.

LEW-11415: Numerical Solution of the Unsteady Navier-Stokes Equations and Applications to Flow in a Rectangular Cavity with a Moving Wall.

LAR-12044: A Program for Contouring Randomly Spaced Data.

MQM-10925: Computational Techniques for Solar Wind Flows Past Terrestrial Planets.

Appendix C: SOURCES

SOURCES

The following information was obtained from the UTSI library and can be used for further source material. The prefactory index code is the accession number.

A80-49257. The Use of Digital Image Analysis in Optical Flow Measurements. M. A. Hernan and J. Jimenez. 1979.

A87-13896. Computer Aided Processing of Flow Visualization Data. J. Rathousky and P. Hampl. 1986.

A86-38241. A Microcomputer System for Real Time Digitized Image Compression. C. S. Moraitis and J. G. Maistros. 1985.

A86-17416. Fast Image Processing with Microcomputer Applied Speckle Photography. R. Erbeck. 1985.

A85-47118. Quantitative Three-Dimensional Flow Visualization. L. Hesselink, J. Pender, S. M. Jaffey, and K. Dutta. 1983.

A85-20852. Application of Digital Interferogram Evaluation Techniques to the Measurement of Three-Dimensional Flow Fields. F. Baker and Y. H. Yu. 1985.

A82-20796. A New Method to Determine Small Density Gradients. W. Frank. 1980.

A81-18018. Measurements of Wavenumber-Celerity Spectrum in Plane and Axisymmetric Jets. A.K.M.F. Hussain and A. R. Clark. 1981.

The following is a VKI referenced publication:

RAE TR 69119. Smith. 1969. "Remarks on the Structure of Conical Flow".

The following are referenced in NASA SP-7045, June 1981, Data Bases and Data Base Systems.

a) N78-19781 & N76-16827: 3-D aero. & "ADAIS" interactive graphics.
b) N75-31551: "TERSSE" re. STS R/S
c) A77-48878: MIDISS w/ Spacetalk on Spacepipe
d) N80-26356: DSS #13 & #11, remote ops. @ Goldstone
e) N78-30829: SSRLATV comm. w/NAT, 21-59.

VITA

Charles Stephen Sanford, EIT, Master of Science candidate, was educated at the University of Tennessee - Knoxville (UTN) BS-E, 1979, and at Vanderbilt University, 1964 through 1968.

His present employment is as an Environmental Engineer for Tennessee Department of Public Health, Construction Grants and Loans, Planning and Design Section with duties including: technical liaison with municipal, industrial, state and federal officials; planning and conducting meetings with documentation of correspondence and conversations; establishing cooperative and effective working relationships with public agencies; and calculating cost effective decisions for the present worth of EPA grant alternatives.

He has two years engineering experience as an Information Analyst and as an Engineer-in-Training for the Tennessee Department of Employment Security, Division of Unemployment Insurance, Special Projects Section with duties including data compliation and analysis on a personal computer for legislative impact on cash flow, and maintenance of a joint federal-state computer data base. Mr. Sanford has one year experience as a Graduate Research Assistant in the Remote Sensing Division at The University of Tennessee Space Institute with duties having included classification and mapping of wetlands for the USACE (Corps of Engineers). He has one year as a Mechanical Engineer for I. C. Thomasson Associates, Incorporated, with duties including engineering consulting for energy management for the Tennessee Valley Authority. He has spent approximately one year as a Mechanical Engineer (Assistant Test Director) for the

Department of Defense, Naval Sea System Command, Naval Sea Weapon Systems Engineering Station with duties including project monitoring for research, development, test and evaluation of the Vertical Launching System where emphasis was on military standards and contract weapon specifications for missile launching. He has two years experience as a Technologist with the Tennessee Department of Public Health, Division of Air Pollution Control, Special Projects Section with duties including maintenance of a joint state-federal data base.