DYNAMIC DETERMINATION OF THE AIR CONTENT IN HIGH PRESSURE FLUID SYSTEMS THROUGH SONIC VELOCITY MEASUREMENT

By

LARRY ROGER ELLIOTT

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1972

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
July, 1974

DYNAMIC DETERMINATION OF THE AIR CONTENT IN HIGH PRESSURE FLUID SYSTEMS THROUGH SONIC VELOCITY MEASUREMENT

Thesis Approved:

E C Fitch Jr.
Thesis Adviser

James E Bose

R L Lowery

N N Durham
Dean of the Graduate College

PREFACE

This study is concerned with the presence of air in high pressure fluid systems, the undesirable effects it has on the system, and the measurement of the local speed of sound in the fluid to provide an accurate indication of the amount of air in the fluid. This measurement of the acoustic velocity can provide an accurate estimate of the entrained air content in a given fluid. When coupled with the theoretical relationship between acoustic velocity, density and bulk modulus, this measurement provides an "in-line" evaluation of the apparent bulk modulus within a section of an operating fluid power system.

I wish to express my sincere appreciation and thanks to the following people and organizations who have encouraged and supported me during my Master of Science program:

Dr. E. C. Fitch, who served as my major advisor. His interest, encouragement and advice were invaluable throughout my graduate study.

Mr. G. E. Maroney, who served as program manager for the acoustics section of the Fluid Power Research Center. Knowing how many hours he spent working on the never-ending problems presented to him made the time I spent at the research center seem nominal.

Mr. T. G. Snyder, because without Greg the experimental evaluation of the concept discussed would have never become a reality.

Dr. Richard Lowery and Dr. James Bose for their valuable assistance in the preparation of the final manuscript.

The staff of the Fluid Power Research Center for their continuing aid in my quest for advanced graduate standing.

My parents, who gave me financial and moral support for more years than they expected.

Dr. M. M. Reischman, whose interest in my personally provided the desire to go to Graduate School and who was the originator of the final and most important acknowledgement. . .

Especially to my wife and typist, Nancy, for prolonged forbearance throughout.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

NOMENCLATURE

C	acoustic velocity
g_c	acceleration conversion factor
M	mass
O	opacity
P	pressure
T	temperature
T_l	time lag
V	volume
β	bulk modulus
ρ	density
$\%Ae$	percent by volume of entrained air

The following subscripts may be applied to any of the variables above.

a	entrained air
d	dissolved air
f	fluid (oil)
i	injection
t	total
s	solution (system)

CHAPTER I

INTRODUCTION

Fluid power system design has become an exacting engineering field which requires a thorough knowledge of the physical parameters that affect the life, operation and control of hydraulic systems. The demand for precisely designed fluid power systems has indicated a need for a more thorough understanding of how air in hydraulic oil affects the system and its individual components.

Qualitatively, a great deal is known about the effects of air in hydraulic oil. A summary of the more prevalent results of this phenomenon is given in Figure 1.

The bulk modulus of the fluid is decreased drastically upon the introduction of small amounts of air in the fluid (16). The bulk modulus (β) is the reciprocal of compressibility and a measure of the stiffness of the fluid in an operating system. One consequence of lowering the bulk modulus in a system is the introduction of a time lag into the operation of the system. The system may become "spongey" and less easily controlled. The bulk modulus (higher compressibility) of an air-oil mixture requires increased system horsepower to compress the elastic fluid to the working pressure desired.

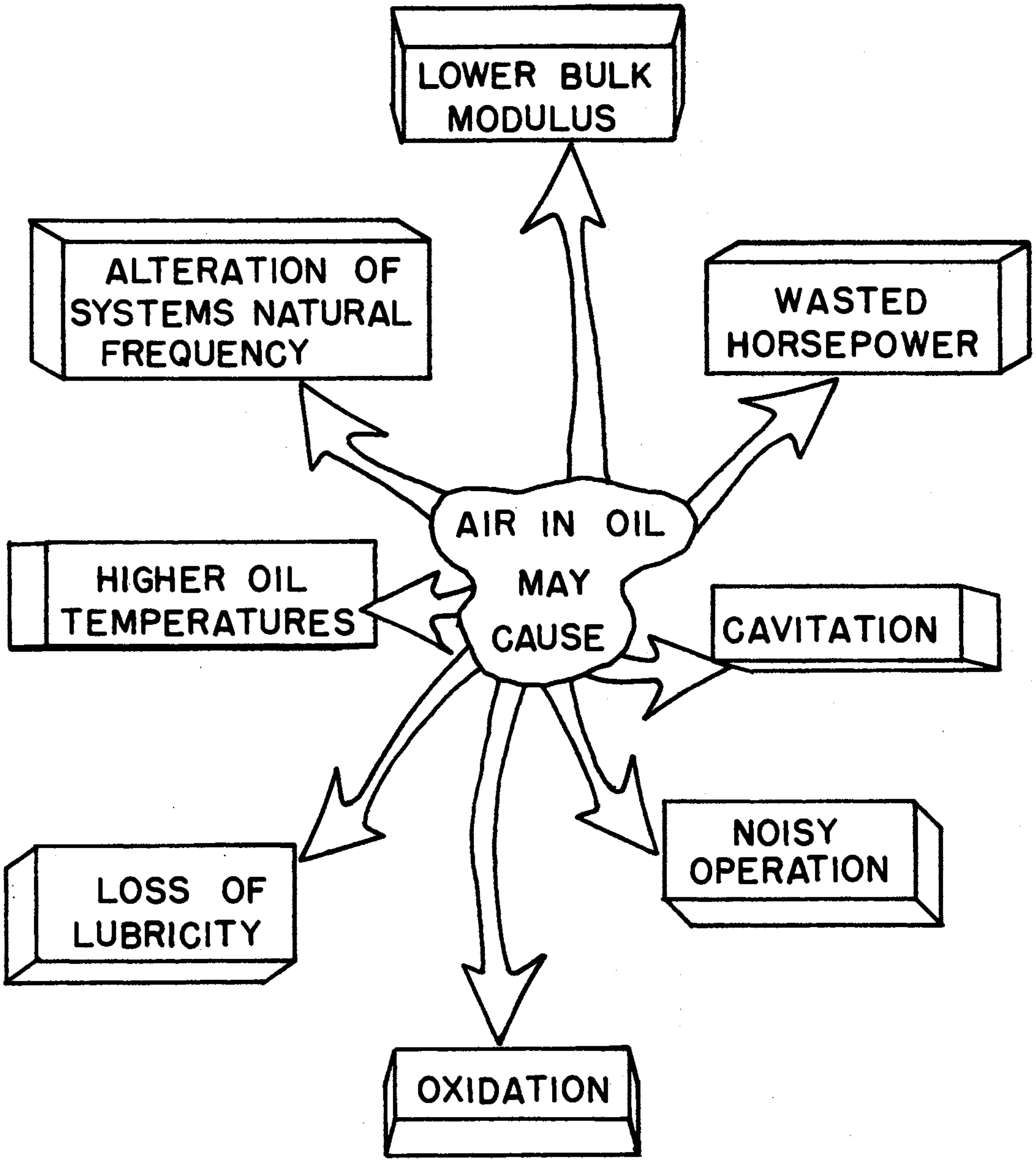


Figure 1. Some Results of Air in Hydraulic Oil

When air is compressed it releases heat. The heat expelled from the air being compressed must be absorbed by the oil. This additional source of heat can cause a system to operate well above the temperature at which it was designed to function, thereby increasing the likelihood of premature failure.

The stability of fluid power systems is to some degree dependent upon the natural frequency of the system (17). The acoustic velocity in the fluid may be altered from approximately five thousand feet per second to fifteen hundred feet per second from the introduction of less than ten per cent by volume of air into the oil. Although changing the natural frequency of a open loop fluid power system used for power transfer by a factor of slightly more than three will not force the system to instability, a three to one variation of natural frequency in a complex automatic system may render the system inoperable.

Cavitation is the formation of gas or vapour pockets in a fluid. The collapse of these pockets can cause severe damage to the exposed surfaces of components. There are several theories concerning the physics of cavitation and all agree that the likelihood of cavitation occurring is increased when air is introduced into the working fluid. Cavitation can be such a destructive phenomenon that a fluid power component may be forced to failure in a matter of minutes (9).

The availability of air, hence oxygen, in the oil of a system increases the oxidation rate of the components. Solid reaction products and acids may be formed causing clogging, rusting and corrosion of the system hardware. The increased oxidation rate and oxidation reaction products can cause premature failure of system components.

Many of the components in fluid power systems rely on the hydraulic fluid to provide lubrication. Introduction of air into the fluid can cause foaming. Foam in the oil reduces its ability to lubricate (24). This reduction in lubricity can cause premature component failure.

It has been postulated that air in the working fluid of a hydraulic system results in higher system sound levels. The sound produced by fluid power systems has recently come under the scrutiny of industry. This author has qualitatively verified that air can cause increased fluid power system sound levels; however, quantitative information is not available at this time.

It is obvious that air in the working fluid of a fluid power system can produce many situations which will result in system failures - situations not likely to occur if air were not present. There are several directions that may be taken to solve problems concerning air in hydraulic fluid.

One obvious solution is to remove any air that is present in the oil. The air can be removed from the fluid by several techniques, which include; 1) screening the bubbles out of the fluid in the reservoir, 2) mechanically degassing, and 3) replacing of the oil (6). Air removal techniques require an additional component in the system, or down time while the oil in the system is replaced. Furthermore, the failure of components due to air in the oil may take place before the air is removed from the system.

One solution to this dilemma is to design fluid power components which will withstand prescribed amounts of air in the oil. Designing fluid power components to withstand given amounts of air is predicated on the availability of quantitative information concerning the amount of air in the fluid of a system. If proper care is taken to establish the air content in the oil, the ability of a component to operate in an air-oil mixture can be emperically derived.

Evaluation of the operating characteristics of fluid power components when subjected to air-oil mixtures may be accomplished in two ways. The components may be installed in a laboratory test system in which a known air-oil mixture can be maintained. Or the amount of air in a given system can be measured during the evaluation of a component. Laboratory test systems would perform well for component evaluation even though the cost of constructing such a system is high. Evaluation of the operating characteristics of a total system when subjected to various air-oil mixtures must rely on a measurement of the quantity of air in the oil. The availability of a technique to measure the amount of air in hydraulic fluid would eliminate the necessity of expensive test systems and provide a means of evaluating the operational characteristics of any fluid power system or component with respect to the amount of air in the oil.

The remainder of the report will consider the possible means by which the amount of air in hydraulic oil may be measured, a theoretical development which provides a basis for one measurement technique, an experimental evaluation of that technique, and conclusions and recommendations concerning the results of the experimental phase of the project discussed in this report.

CHAPTER II

PARAMETRICAL EFFECTS OF AIR ON OIL

The presence of air in hydraulic fluid has some affect on virtually all of the fluid properties of oil. The initial investigation performed during the project discussed in this report was to determine which of the fluid properties were the most promising as indicators of the amount of air present in the working fluid of a system. The four properties listed were considered as possible parameters to be used as indicators of the amount of air present: bulk modulus (β), density (ρ), opacity (o), and acoustic velocity (c). Each of these parameters were investigated with respect to their range of variation in the presence of both dissolved and entrained air. Dissolved air is that air which is in solution, and entrained air is in the form of small bubbles in the fluid.

As mentioned previously, the bulk modulus of a fluid varies over a large range as small amounts of air are introduced. According to all of the pertinent literature on the subject of air in oil, the presence or absence of dissolved air in the fluid does not affect the bulk modulus. According to V. G. Magorien (16), "If one visualizes a container filled to the brim with marbles (which represent the oil molecules), it is possible to pour fluid (representing air) around them, or remove the fluid with no change in the volume." The presence of entrained air (small bubbles) does, however, change the volume and the bulk modulus. Figure 2 illustrates the magnitude of reduction in bulk modulus than can be expected from small amounts of entrained air in the fluid. The large range of variation of bulk modulus indicates that the bulk modulus of a fluid can provide an accurate estimate of the air content in that fluid. The only drawback is the determination of the bulk modulus of a fluid. Accurate measurement of the bulk modulus is difficult and requires that the fluid be confined in a pressure cylinder under static conditions (27). This type of analysis does not lend itself well to use with operational fluid power systems. It is for this reason that the measurement of bulk modulus was rejected as a possible means of determining the air content in a fluid.

Fluid density (ρ) was the second parameter considered as a possible measure of the amount of air in the fluid. Density is affected by both dissolved and entrained air, as illustrated in Figure 3. Hydraulic fluids will dissolve approximately ten per cent by volume of air before the addition of;more air forms bubbles (entrained air) in the fluid (1). Dissolved air does not affect the volume of the fluid, however it does increase the weight. Consequently, the density of the fluid increases slightly as the fluid dissolves air up to its saturation level. Additional air must become entrained, which increases the volume of mixture and decreases the density. The variation of density over the

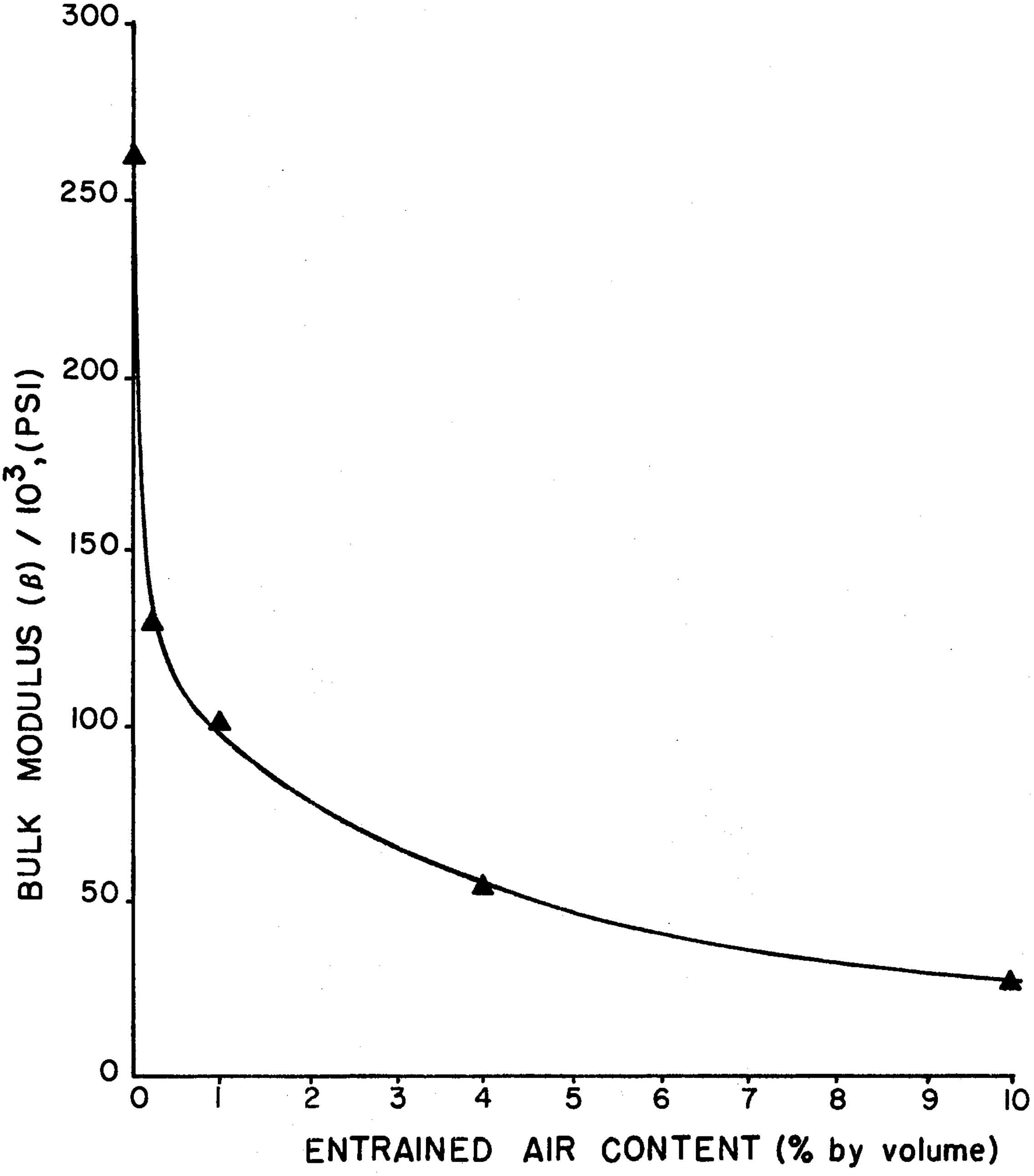
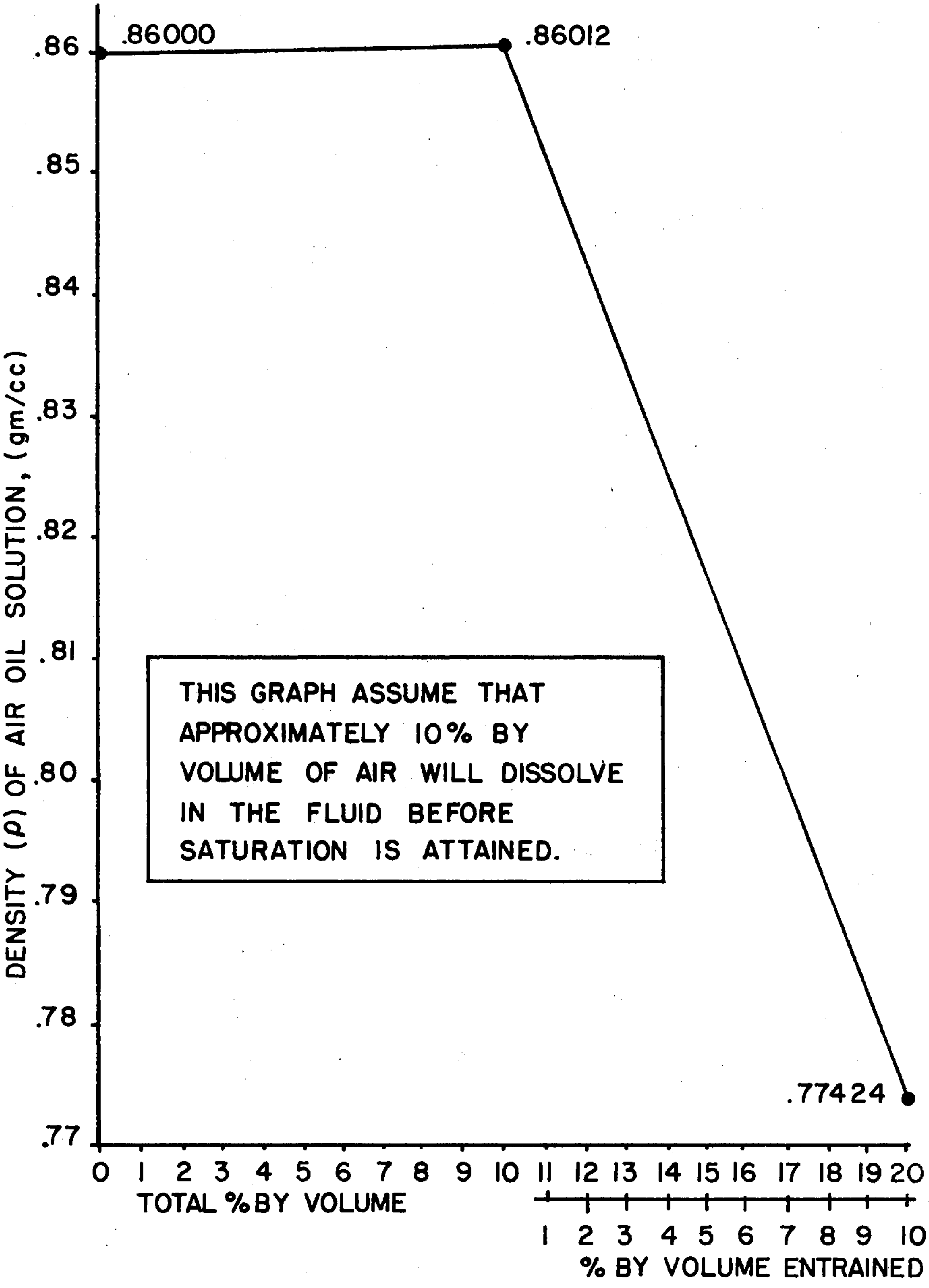


Figure 2. Bulk Modulus Variation with Respect to % Entrained Air



THIS GRAPH ASSUME THAT APPROXIMATELY 10% BY VOLUME OF AIR WILL DISSOLVE IN THE FLUID BEFORE SATURATION IS ATTAINED.

Figure 3. Variation of Density upon Addition of Air to Oil

same range of entrained air is two orders of magnitude less than that of bulk modulus. However, an "in-line" technique for measuring fluid density is available. The technique is based on the variation of the natural frequency of a hollow tuning fork, as the density, hence mass, of the fluid passing through the tube varies. Lack of funding precluded the evaluation of this technique. It is recommended that any further studies concerning the measurement of air in oil consider this type of measurement due to its ease of implementation and the linear dependence of fluid density on air content.

Fluid opacity is the third parameter to be considered as a measure of the amount of air present in a fluid. The opacity of a fluid is easily measured with a high intensity light source and a photo detector. This type of measurement is being investigated at the Fluid Power Research Center in conjunction with the project discussed herein. A qualitative indication of its applicability for measuring the amount of air in oil may be gained from the information presented in Figure 4. The opacity of the fluid is not affected by dissolved air. As the amount of entrained air increases the opacity of the fluid increases.; One obvious limitation to this type of measurement is the necessity to calibrate the instruments for each type of fluid used.

The acoustic velocity in the fluid (c) is the final parameter that was considered as a possible measure of the quantity of air in the fluid. The acoustic velocity in a fluid is a function of the fluid density and bulk modulus (27). The three parameters are related by Equation 1.

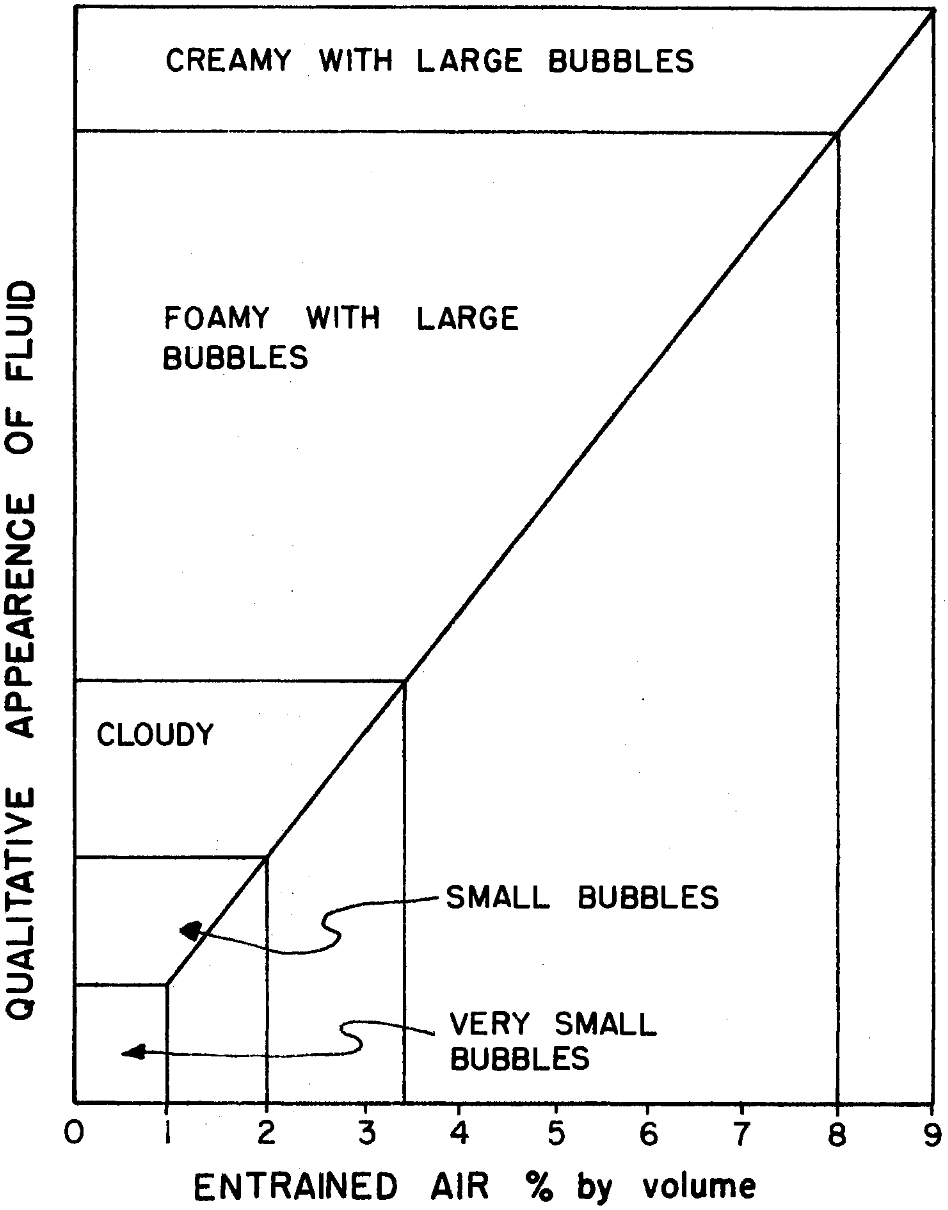


Figure 4. Qualitative Appearance of MIL-L-2104-B with Various Amounts of Entrained Air

$$\beta = \rho c^2 \qquad (1)$$

The acoustic velocity in hydraulic fluid varies from approximately five thousand feet per second when no entrained air is present, to approximately fifteen hundred feet per second when there is ten per cent by volume of entrained air in the fluid. Dissolved air does not affect the bulk modulus of a fluid and only slightly affects the density; therefore, it has no appreciable affect on the acoustic velocity. The range of variation of the acoustic velocity (3:1) is proportionately greater than that of density (1.1:1) and less than that of bulk modulus (10:1). The acoustic velocity in a fluid is easily measured with two pressure transducers and an oscilloscope, assuming that a pressure wave may be generated in the fluid. This technique will be developed in more detail in the next chapter and an experimental evaluation of its applicability will be presented in Chapter IV.

CHAPTER III

THEORETICAL EFFECTS OF AIR CONTENT ON THE ACOUSTIC VELOCITY IN A FLUID

Before presenting a discussion of the effect of air on the fluid properties of oil, it is appropriate to discuss what is meant by the amount of air contained in a fluid. It is generally accepted that dissolved air has no appreciable effect on the fluid properties of oil that are pertinent to this discussion. This can be shown to be true for fluid density, which changes from .86 gm/cc to .86012 gm/cc when saturated with dissolved air at standard temperature and pressure (STP = 760 mm Hg & 20°C). The dependency of bulk modulus of dissolved air is assumed to be negligible. This assumption is consistent with all previous investigations. It may be said, then, that the fluid properties in question, density and bulk modulus, are proportional to the amount of entrained air. Any further reference to the amount of air in a fluid will refer to the amount of entrained air in the fluid unless otherwise stated and will assume that the fluid is saturated with dissolved air at the fluid condition of pressure and temperature.

The definition of the sonic bulk modulus indicates the dependency of the acoustic velocity in a fluid on the bulk modulus and density of the fluid. The sonic bulk modulus is identical to the isentropic tangent bulk modulus defined in Equation 2.

$$\beta t = -V\left[\frac{\delta P}{\delta V}\right]_s \tag{2}$$

Since the isentropic tangent bulk modulus and sonic bulk modulus are identical (27):

$$\beta t = -V\left[\frac{\delta P}{\delta V}\right]_s = \rho c^2. \tag{3}$$

Equation 3 may be solved for the acoustic velocity in terms of the isentropic bulk modulus and fluid density.

$$c = \left[\frac{\beta t}{\rho}\right]^{\frac{1}{2}} \tag{4}$$

A relationship which presents the acoustic velocity in the fluid in terms of the air contained in that fluid may be derived by determining the relationship between both the bulk modulus of an air-oil solution (β_s) and the density of an air-oil solution (ρ_s) with respect to the quantity of air contained in the fluid.

Density as a Function of Air Content

Density is defined as the mass of a particular substance divided by its volume,

$$\rho = \frac{M}{V} \tag{5}$$

where M equals mass and V equals volume. For an air-oil solution the density of the solution (ρ_s) is the mass of the air plus the mass of the fluid divided by the volume of the solution.

$$\rho s = \frac{M_A + M_F}{V_s} = \frac{M_A}{V_s} + \frac{M_F}{V_s} \tag{6}$$

Since:

$$M = \rho V \tag{7}$$

the density of an air-oil solution is,

$$\rho s = \rho a \frac{V_A}{V_s} + \rho f \frac{V_F}{V_s}. \tag{8}$$

Furthermore,

$$V_s = V_A + V_F \tag{9}$$

and

$$V_F = V_s - V_A. \tag{10}$$

Substituting Equation 10 into Equation 8, one obtains Equation 11,

$$\rho s = \rho a \frac{V_A}{V_s} + \rho f \frac{(V_s - V_A)}{V_s} \tag{11}$$

which may be reduced to,

$$\rho s = \frac{V_A}{V_s} (\rho a - \rho f) + \rho f . \tag{12}$$

Equation 12 was used to generate the curve found in Figure 4. The amount of dissolved air has very little affect on the density of the solution (.014% maximum @ STP). The amount of entrained air does affect the density of the solution (ρ_s) due to the significant alteration of the volume of the solution.

Bulk Modulus as a Function of Air Content

Determination of the relationship between bulk modulus and air content for a fluid is somewhat more difficult than for that of density. A simple derivation of a bulk modulus prediction technique for air-oil mixtures, as presented by Rendel and Allen (21), will be used to illustrate the inadequacies of present theory to produce reasonable results for fluids that contain air.

The bulk modulus of the fluid is defined as:

$$-\beta_f = V_f \left[\frac{dP}{dV}\right] . \tag{13}$$

The bulk modulus of air in the same terms is,

$$-P = V_A \left[\frac{dP}{dV}\right] \tag{14}$$

or, according to Rendel and Allen (21),

$$-\beta A = -\frac{P^2}{Po} = Vo\left[\frac{dP}{dV}\right] . \tag{15}$$

Equations 14 and 15 may be solved for (-dV/dP) to get Equations 16 and 17, respectively.

$$-\frac{dV}{dP} = \frac{Vf}{\beta f} \tag{16}$$

$$-\frac{dV}{dP} = \frac{PoVa}{P^2} \tag{17}$$

Rendel and Allen (21), the authors of the paper in which this derivation is presented, make the following statement prior to the next step in the derivation of their prediction technique. "In order to consider the elasticity of mixture of air and oil it is necessary to combine these two equations." (21) The two equations they refer to are presented here as Equations 16 and 17. They combine them by adding the two together to get:

$$-\frac{dV}{dP} = \frac{V_F}{\beta f} + \frac{PoVa}{P^2} \; . \qquad (18)$$

This is a critical step in the derivation and should be noted, as this linear combination is contrary to the physics of the air-oil compression mechanism. A thorough discussion of the results of this assumption is presented later in this chapter.

The bulk modulus of an air-oil mixture may be defined as:

$$-\beta s = V_s \left[\frac{dP}{dV}\right] . \qquad (19)$$

Since,

$$V_s = V_F + V_A \qquad (20)$$

then,

$$-\beta s = (V_F + V_A)\left[\frac{dP}{dV}\right] . \qquad (21)$$

Solving for (-dV/dP),

$$-\frac{dV}{dP} = \frac{V_F + V_A}{\beta s} \; . \qquad (22)$$

The right sides of Equations 18 and 22 may now be set equal to get

$$\frac{V_F}{\beta f} + \frac{PoVa}{\rho^2} = \frac{V_F + V_A}{\beta s} \; . \qquad (23)$$

By solving for the bulk modulus of the solution (β_s), the final result is produced.

$$\beta s = \frac{\beta_f \, (1 + Va/Vf)}{1 + \frac{Va}{Vf} \frac{Po}{P^2} \, \beta^f} \quad . \tag{24}$$

Remembering that:

$$\frac{P^2}{Po} = \beta A \tag{25}$$

and,

$$Vf = Vs - Va \tag{26}$$

then,

$$\beta s = \frac{\beta f \, (1 - Va/Vs) + Va/Vs}{(1 - Va/Vs) + \frac{Va}{Vs} \left[\frac{\beta f}{\beta a} \right]} \tag{27}$$

The bulk modulus of the air-oil solution is now a function of the bulk modulus of the air, and bulk modulus of the oil, and the volume ratio of the air and oil. The prediction technique derived in Equations 13 through 27, and an empirical equation derived by V. G. Magorien (17) are both depicted graphically in Figure 5. The Rendel-Allen technique predicts significantly higher bulk modulus values for an air-oil mixture than can be obtained with no air in the oil. Magorien's prediction technique is plotted for various air contents and operating conditions in Figure 6.

When either technique is used to predict the bulk modulus of an air-oil mixture for use with the equation

$$C = \left[\beta / \rho \right]^{\frac{1}{2}} \tag{28}$$

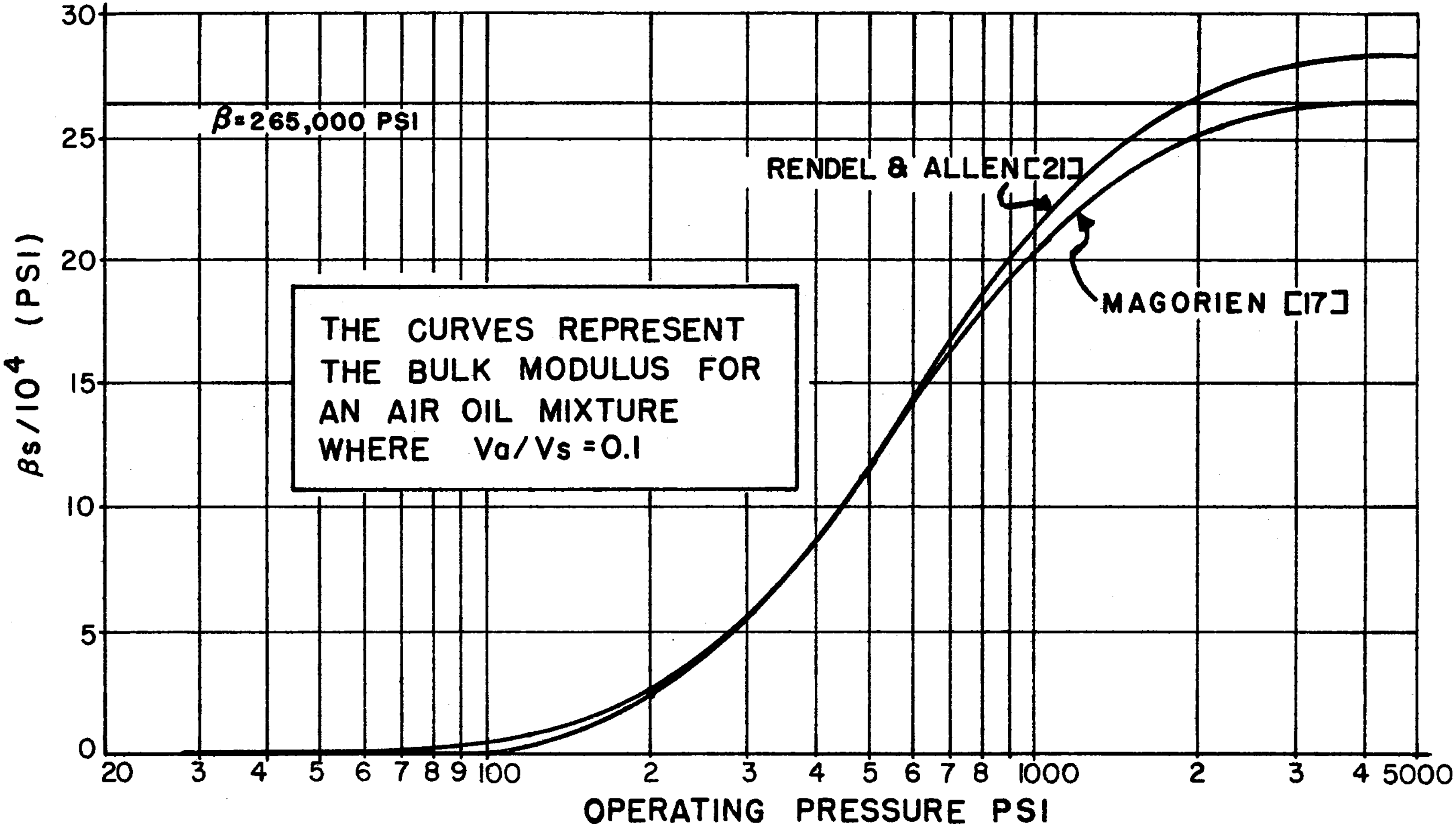


Figure 5. Comparison of Analytical and Empirical Bulk Modulus Prediction Techniques

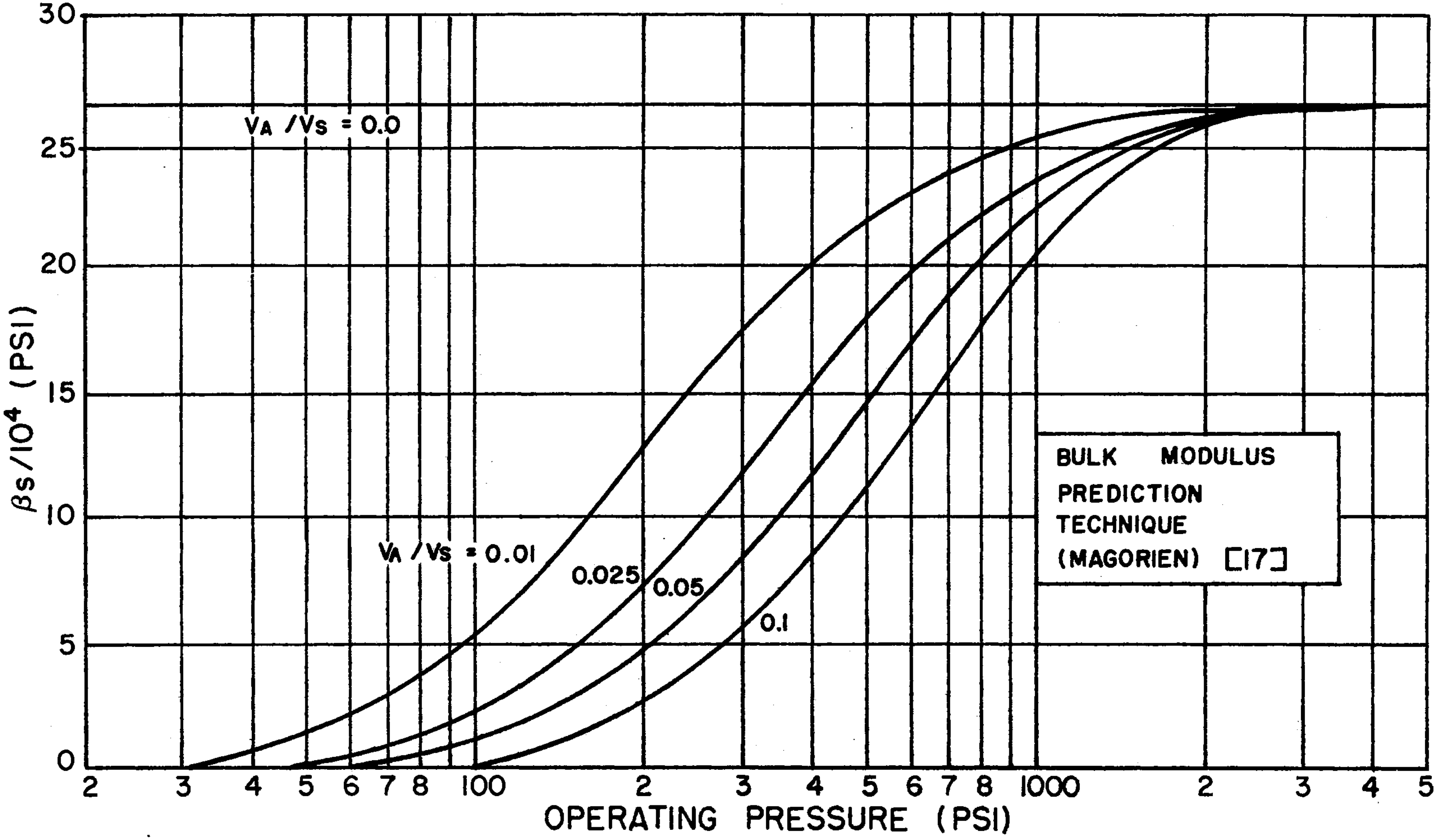


Figure 6. Variation of Bulk Modulus with Respect to Entrained Air Content

the calculated acoustic velocities are below the physically allowable limit (that of approximately 1100 ft/sec for 100% air). The unquestionably low acoustic velocities are the result of incorrect bulk modulus estimation.

The assumption that the bulk modulus of the fluid and the bulk modulus of the air may be combined in some simple fashion (addition) to produce a prediction technique which accurately estimates the bulk modulus of an air-oil mixture is erroneous. If the air and oil could be treated as separate entities as in Figure 7 the linear combination of Equations 16 and 17 would be valid. This is not the case, however, for air-oil mixtures. At some slightly increased pressure (compared to the normal operating pressure in a hydraulic system, 2000 PSI) the air enters into solution with the oil and no longer affects the compression of the solution. This two-step process is graphically illustrated in Figure 8. A prediction technique based on this knowledge of the physics of the compression of an air-oil mixture could provide a most accurate evaluation technique for the bulk modulus of a solution of air and oil. Wallis (27) discusses the difficulties in formulating a theoretical relationship between the air contained in a fluid and its sonic velocity.

Due to the lack of a theoretically based method for evaluating the bulk modulus of an air-oil mixture, further progress toward the goal of determining the effects of air on the properties of the oil must be empirically derived.

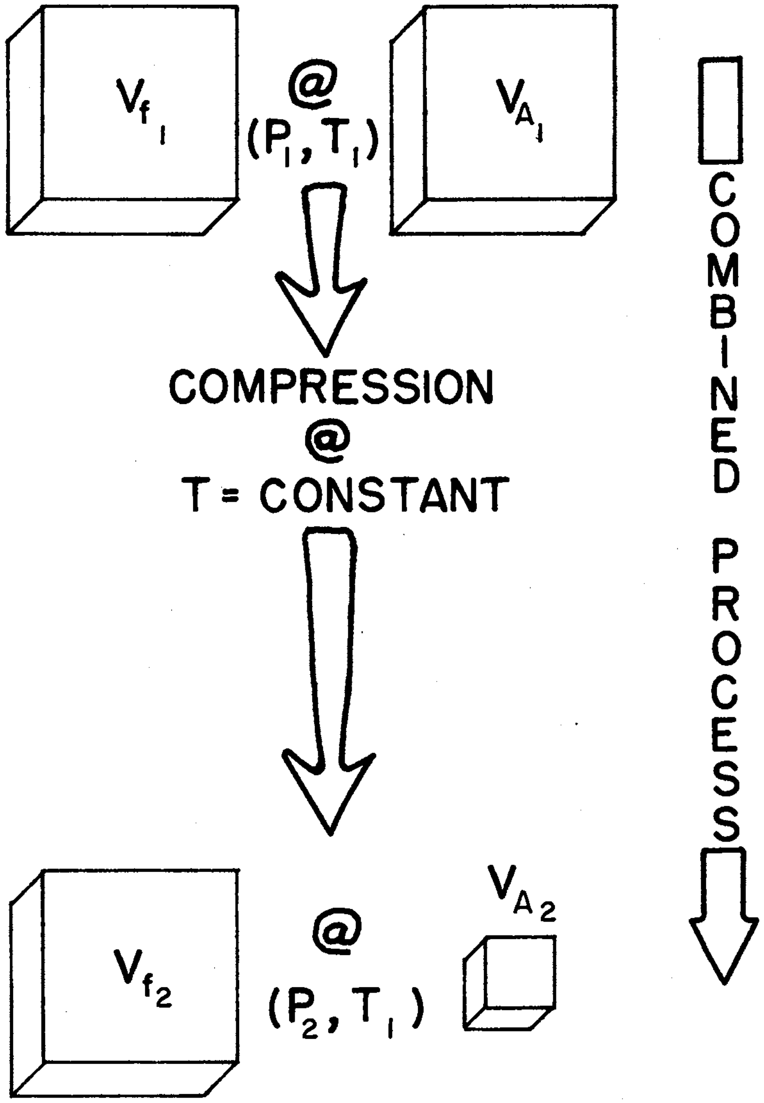


Figure 7. Volume Comparison of Air and Oil Under Compression if Air Does Not Go into Solution

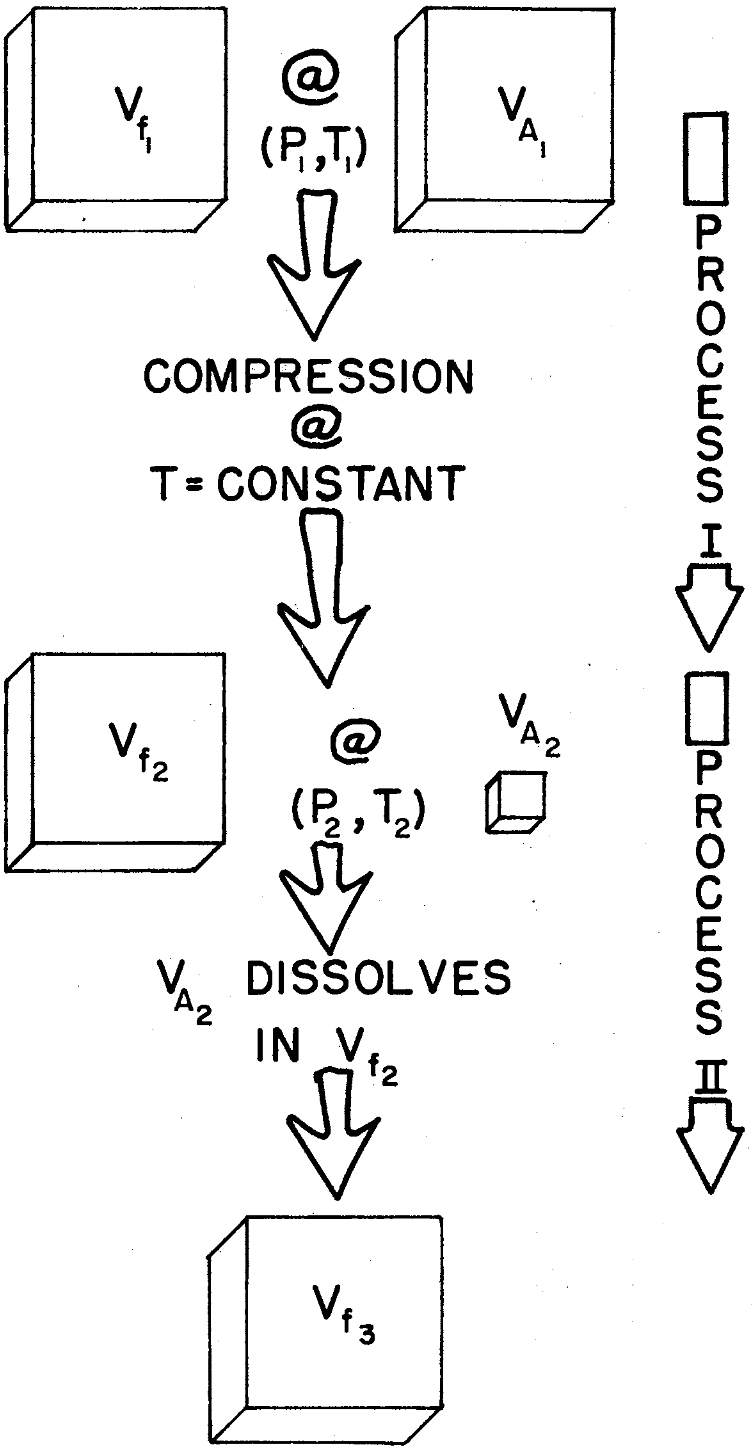


Figure 8. Volume Comparison for Two-Step Compression of Air-Oil Mixture

The next chapter presents a discussion of the experimental phase of the project discussed herein. The experimental portion of the project was designed to provide empirically based knowledge of the relationship between the parameters (β_s, ρ , and c) and entrained air content.

CHAPTER IV

EXPERIMENTAL DETERMINATION OF THE SONIC VELOCITY IN AN AIR-OIL MIXTURE

The experimental phase of the project discussed in this report was conducted in the acoustic laboratory of the Fluid Power Research Center at Oklahoma State University. A special test system was constructed in which a controlled amount of air could be injected into a known volume of oil to obtain a desired level of entrained air in the oil over any desired range of operating conditions. Four of the most important components in the system, with respect to air content control are shown in Figure 9. The purpose of each of the components and a discussion of the remainder of the system may be found in Appendix A.

The system operates as a closed loop after a known volume of air is injected into a known volume of oil. A discussion of how these volumes were determined is presented in Appendix B. The closed flow loop was designed to maintain a homogeneous air-oil mixture without free air pockets.

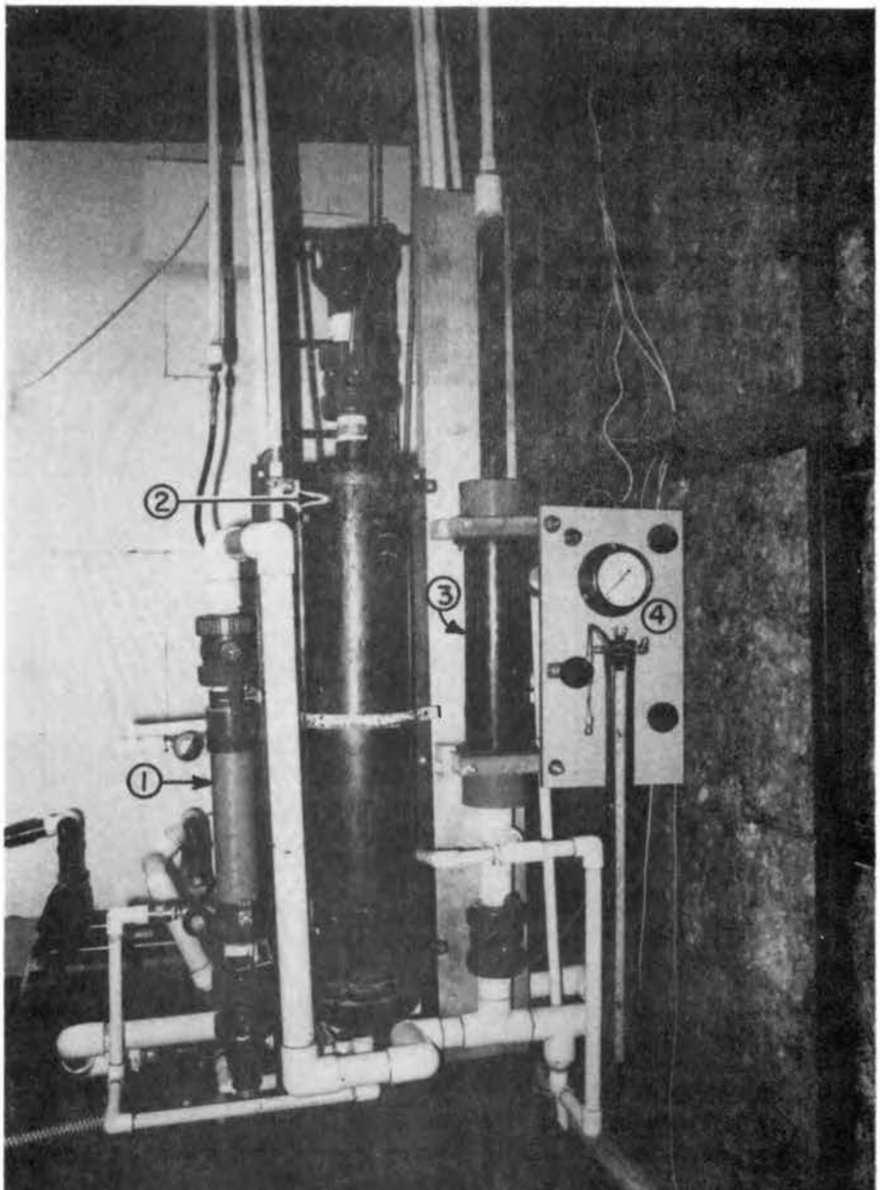


Figure 9. Air Evacuation and Injection Portion of the Test System

1) Air Injection Chamber
2) Storage Reservoir
3) Air Evacuation Reservoir (Evacuation Mode)
4) Injection Chamber Pressure Controls

Experimental Procedure

The initial step prior to measuring the acoustic velocity in the oil was that of evacuating all air from the oil. This was accomplished by circulating the oil in the system through the evacuation reservoir in which a vacuum of twenty inches of mercury was maintained. The evacuation process for the volume of fluid in the test system required from thirty minutes to one hour.

At the completion of the evacuation process it was necessary to measure the amount of dissolved air that was still in the fluid. A dissolved air measurement device (DAMD) was constructed from two syringes (one 50cc and one 2cc), and a stop-cock. The larger syringe is a numbered set which provides the best fit between the plunger and the body. The fit between these two parts is critical due to the way the syringe is used. A sample of oil was extracted from the system and placed in the dissolved air measuring device. By pulling the plunger of the DAMD, a partial vacuum can be created on the oil. This vacuum expands any remaining dissolved air in the oil to form small bubbles that rise to the top of the oil-filled cavity. Care must be taken during this procedure to prevent the leakage of air between the plunger and the body of the DAMD. Once the small air bubbles have collected at the top of the oil the plunger is released to allow the air to compress to its volume at atmospheric pressure. That volume was read from the gradations on the 2cc syringe and the volume of the oil was read on the gradations of the 50cc syringe. This technique was used to verify that the dissolved air content was less than .5% (Vr/Vs less than .005) before each test was initiated. A sketch of the DAMD is shown in Figure 10. The DAMD shown in this drawing was designed and constructed by this author.

After the air has been evacuated from the oil and the remaining dissolved contents are measured, the air evacuation reservoir is shut off from the system. It is removed from the active flow loop to prevent the evacuation of the air that is introduced to the oil in the next step.

The air injection procedure consists of a series of valve openings and closings which perform the purpose of providing a known volume of air (Vi) at a known pressure and temperature (Pi, Ti) that is in a position to be introduced to a closed flow loop containing a known volume of MIL-L-2104B hydraulic fluid. The injection process consists of a few more valve openings and a drive system start-up.

The drive system for the test flow loop is a two-hundred horsepower direct current dynamometer motor operating as a reversable motor. The dynamometer is hydrostatically coupled to the drive shaft of an eight-tooth external gear pump which is the system pump for the test loop. The fact that the pump has eight teeth is of some importance due to its affect on the pumping frequency of the pressure ripple in the fluid line. The frequency of that pressure ripple (fluid borne noise) determines the wave length (λ) of the pressure wave in

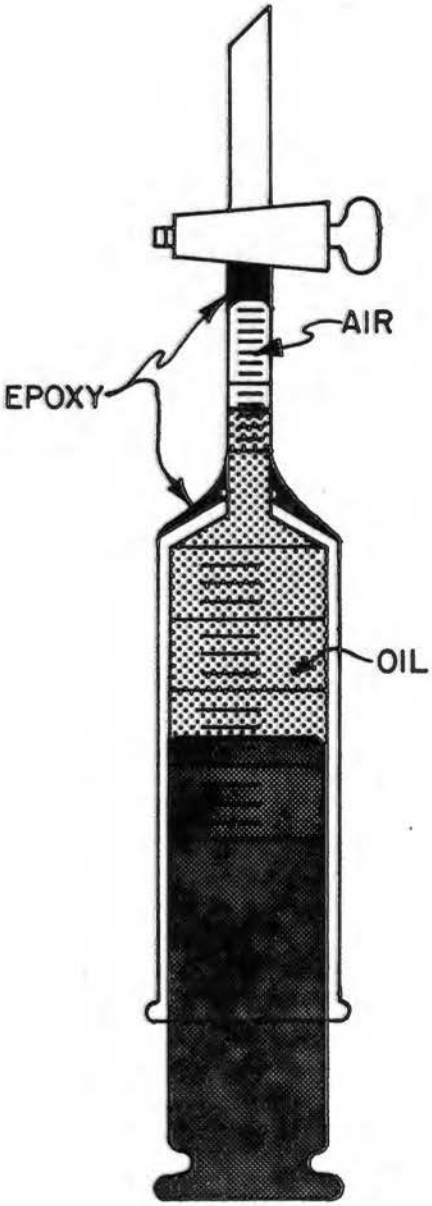


Figure 10. Dissolved Air Measurement Device (DAMD)

the conduit. The range of variation of the wave length of the pressure wave determined the distance between the measurement transducers in the steel conduit lines extending from the inlet and outlet of the pump. The distance between the transducers (L) was set such that sinusodal pressure signals, from the two pressure transducers, in the flow path would never be more than one wave length out of phase when the acoustic velocity of the air-oil medium varied from five thousand feet per second (pure oil, no air) to eleven hundred feet per second (100% air). That distance for an eight-toothed pump operating at 2000 rpm with a basic pumping frequency of 266.6 Hz is:

$$L = 3.5 \text{ feet}. \tag{29}$$

The actual test section is shown pictorially in Figure 11. The low pressure side of the system is to the right of the figure and the higher pressure side of the system is to the left. Both high and low pressure sides of the test loop contained three piezoelectric pressure transducers. The outer two of each set of three was the distance of $L = 3.5$ feet apart.

Thus far in this chapter a procedure that produces a mixture of air and oil from a known volume of air and a known volume of oil and some of the physical make-up of the measurement system have been discussed. The remainder of this chapter contains the measurement procedure that was used for determining the sonic velocity in the fluid of the test loop.

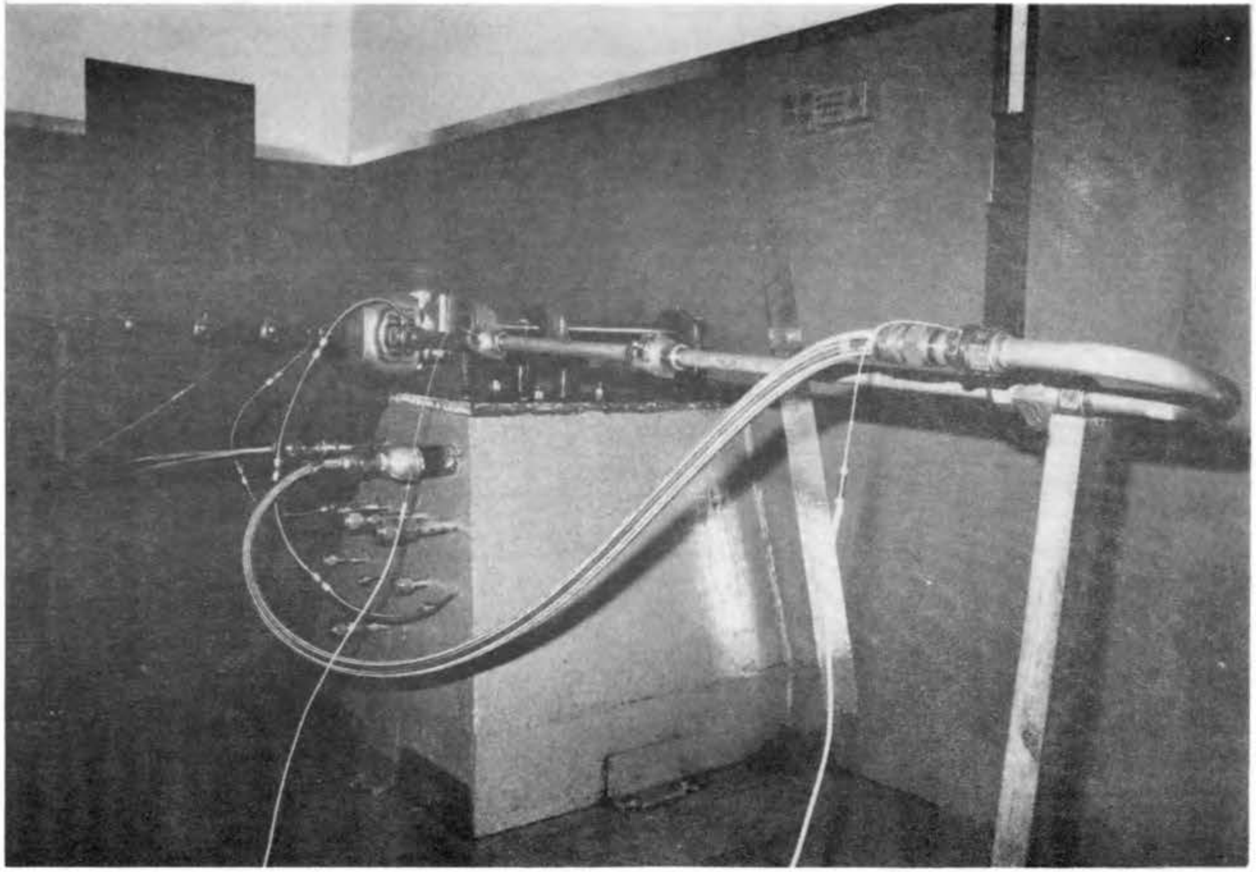


Figure 11. Pressure Transducer Arrangement for Sonic Velocity Measurement

Measurement Procedure

At this point in the experimental procedure an air-oil mixture is flowing in the test circuit. The amount of entrained air an any point in the system is a function of the fluid pressure and temperature. An equation for the entrained air content at any arbitrary system condition is easily derived from the equation of state for a perfect gas and a knowledge of the amount of air that will dissolve in the oil.

$$Pv = Rt \tag{30}$$

From Equation 30, Equation 31 is derived and is valid for perfect gas involved in a reversable isentropic process (18).

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \tag{31}$$

If Equation 31 is solved for V_2 and the appropriate subscripts are added to the variables, Equation 32 may be obtained,

$$V_t = \frac{P_i V_i}{T_i} \frac{T_s}{P_s} \tag{32}$$

where, the subscripts are i = injection chamber condition; s = system condition, and t = total air (entrained plus dissolved).

By adding the amount of residual dissolved air (Vr) left in the oil after degassification of the oil to the volume of the air at the solution condition, and dividing by the volume of the solution, Equation 33 is formed.

$$\frac{Vt}{Vs} = \frac{\frac{PiViTs}{TiPs} + Vr}{Vs} \tag{33}$$

The total volume of air in the fluid is not necessarily the volume of entrained air in the fluid. Hydraulic fluids will dissolve approximately ten per cent by volume of air at the conditions of the fluid before the air begins to become entrained. The amount of air that will dissolve in hydraulic fluid is a function of the viscosity of the oil (20). The viscosity of hydraulic oil is most critically dependent upon its temperature. A plot of the viscosity of MIL-L-2104-C is shown in Figure 12. A relationship between the viscosity of the oil and amount of air that will dissolve in the oil is presented in Figure 13. Figure 13 was empirically derived by personnel of the National Engineering Laboratory of Great Britain (20).

The volume (Vd) of the total air injected into the test system that dissolves in the oil may be determined from the two figures just mentioned and the total volume of the fluid (Vf).

The volume of the air that is dissolved may now be subtracted from the total volume of air injected to determine the entrained air volume ratio (Va/Vs).

$$\frac{Va}{Vs} = \frac{Vt - Vd}{Vs} = \left[\frac{PiViTs}{TiPs} + Vr - Vd\right]\frac{1}{Vs} \tag{34}$$

The volume ratio (Va/Vs) is the non-dimensional parameter against which the fluid parameters will be contrasted during the remainder of

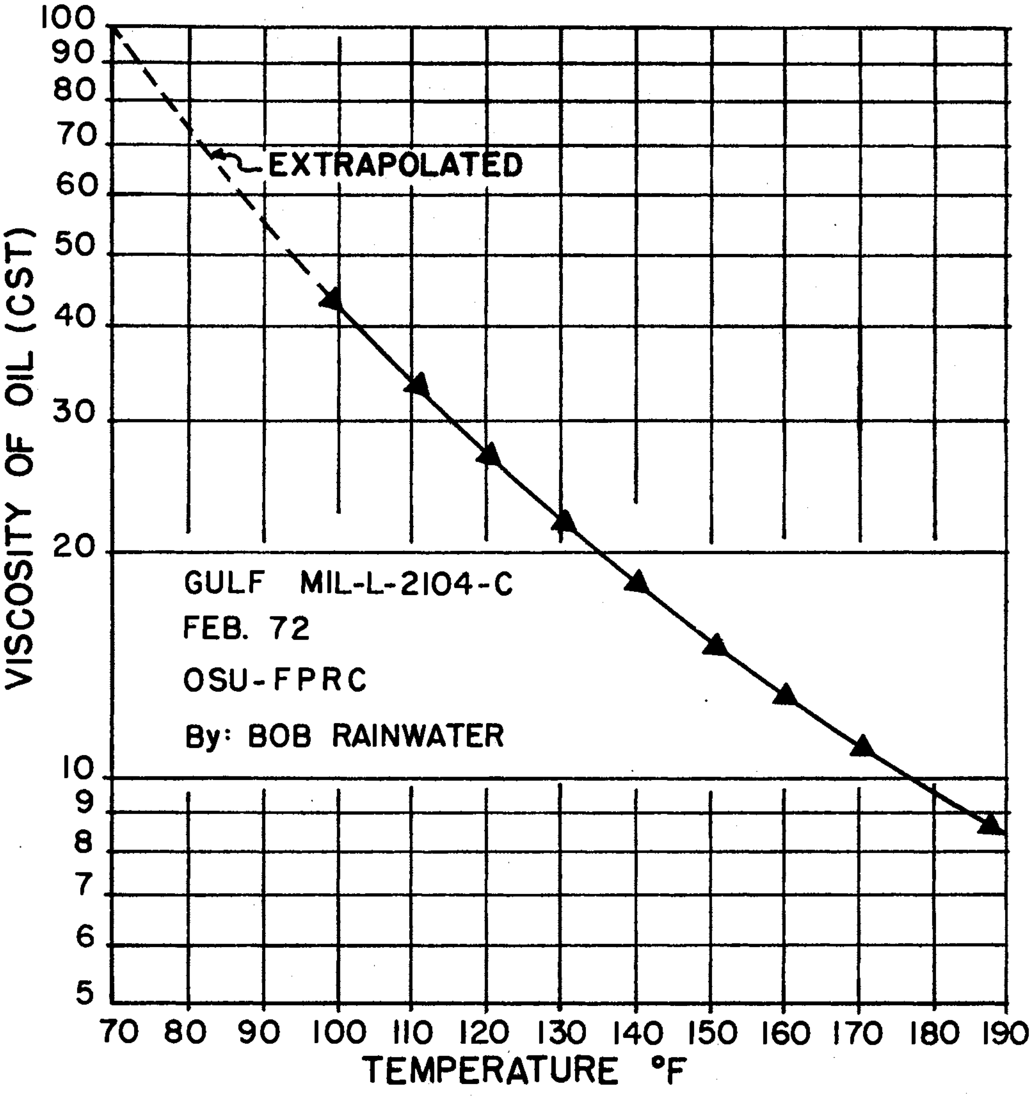


Figure 12. Viscosity of MIL-L-2104-C as a Function of the Temperature

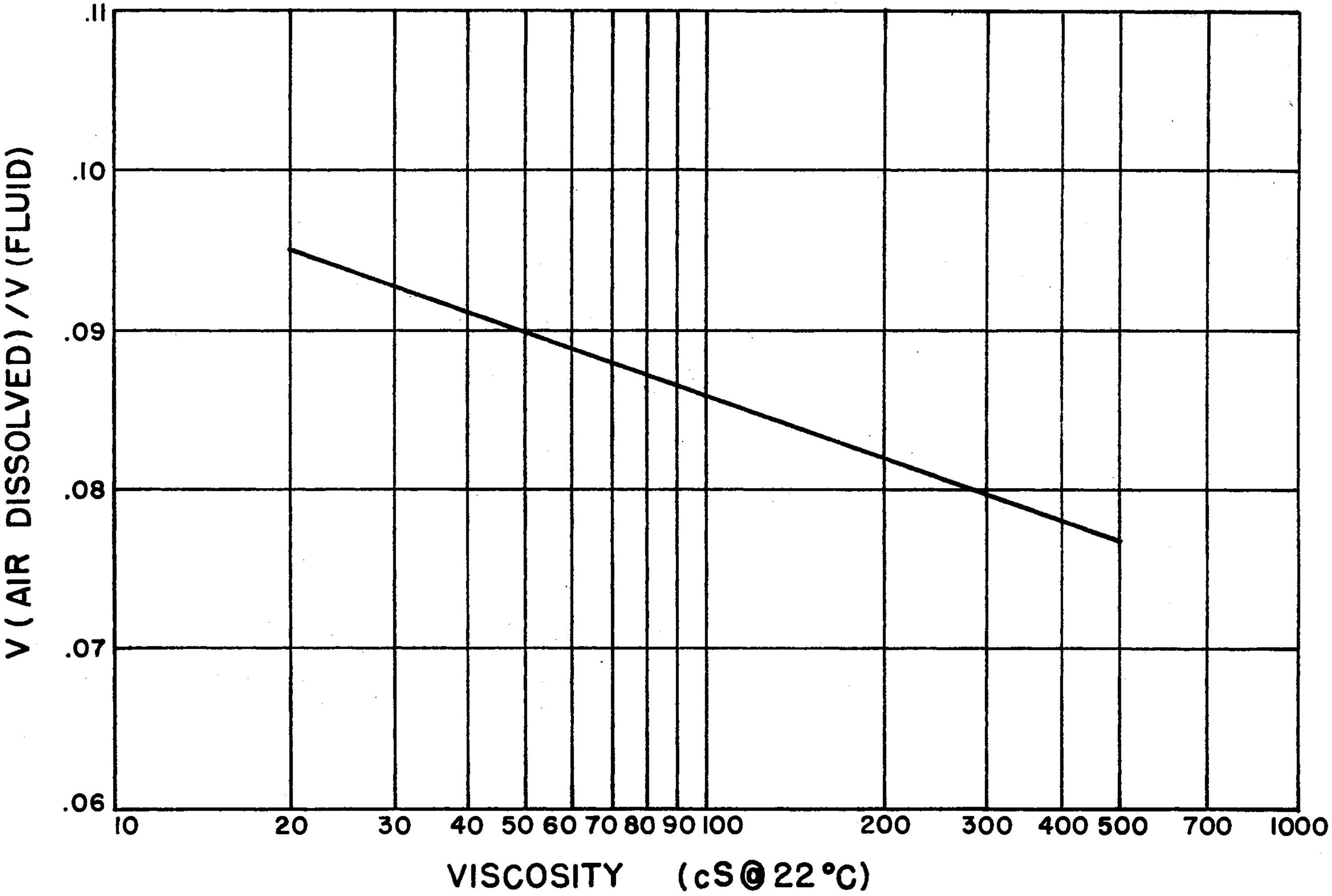


Figure 13. Empirically Derived Relationship Between the Viscosity of Oil and the Volume of Air that will Enter into Solution (20)

this discussion. For simplicity's sake, the volume ratio will not be given a new variable name, but will be represented by (Va/Vs).

The volume ratio, when multiplied by one hundred, is the per cent of entrained air in the fluid.

$$\frac{Va}{Vs} \times 100 = \% Ae \qquad (35)$$

At this point in the experimental procedure the amount of entrained air is known at any fluid condition of pressure and temperature. The next step in the experimental procedure consists of determining the phase shift between the two pressure signals from pressure transducers that are three and one-half feet apart.

Since the sonic velocity of the fluid in the system was to be measured through the determination of the speed of a pressure wave in the fluid, the project was predicated on the production of a pressure wave in the fluid line by the system pump. The project personnel were not disappointed. As mentioned previously, the transducer spacing was set for the operating condition of 2000 rpm for the pump on the assumption that the dominant pressure amplitude would be at the basic pumping frequency of the eight-tooth pump. This assumption was derived from empirical knowledge gained from past fluid-borne noise measurements obtained in the high pressure line of fluid power systems. Most of the measurements for the project discussed in this report were made in the low pressure side of the system. The dominant pressure amplitude for the fluid-borne noise on the suction side of the pump, for the pump used in the test system, is twice the basic pumping frequency of the pump. Due to the fact that the distance between the pressure transducers was fixed, the pump speed was reduced to 1000 rpm to produce a pressure wave in the suction line of the system with a frequency of 266 Hz.

The two pressure sygnals were passed through separate low pass filters set to reject the frequencies above 250 Hz. Electronic filtering of the pressure signals smoothed the wave form to allow more easily locating the peaks of the pressure wave on the face of an oscilloscope.

The velocity at which the pressure wave propagates away from the pump is the acoustic velocity in the fluid (c). The acoustic velocity in the fluid may be determined by dividing the distance between the pressure transducers by the time lag between the two pressure waves. The average time lag between the two pressure signals was estimated by determining the mean of ten measurements of the instantaneous time lag between the signals. This instantaneous time lag was determined by displaying the two pressure signals on the face of a dual beam storage oscilloscope. The acoustic velocity in the fluid may be determined from the following equation.

$$C = \frac{L}{TL} = \frac{3.5 \text{ feet}}{TL} \tag{36}$$

The acoustic velocity of air-oil mixtures ranging from 0% to 10% of entrained air were obtained by this method. Photographs of the oscilloscope's face displaying the two filtered pressure signals are presented in Figures 14 and 15. These photographs portray various fluid conditions.

The results obtained through the use of the experimental procedure discussed in this chapter will be presented in the next chapter.

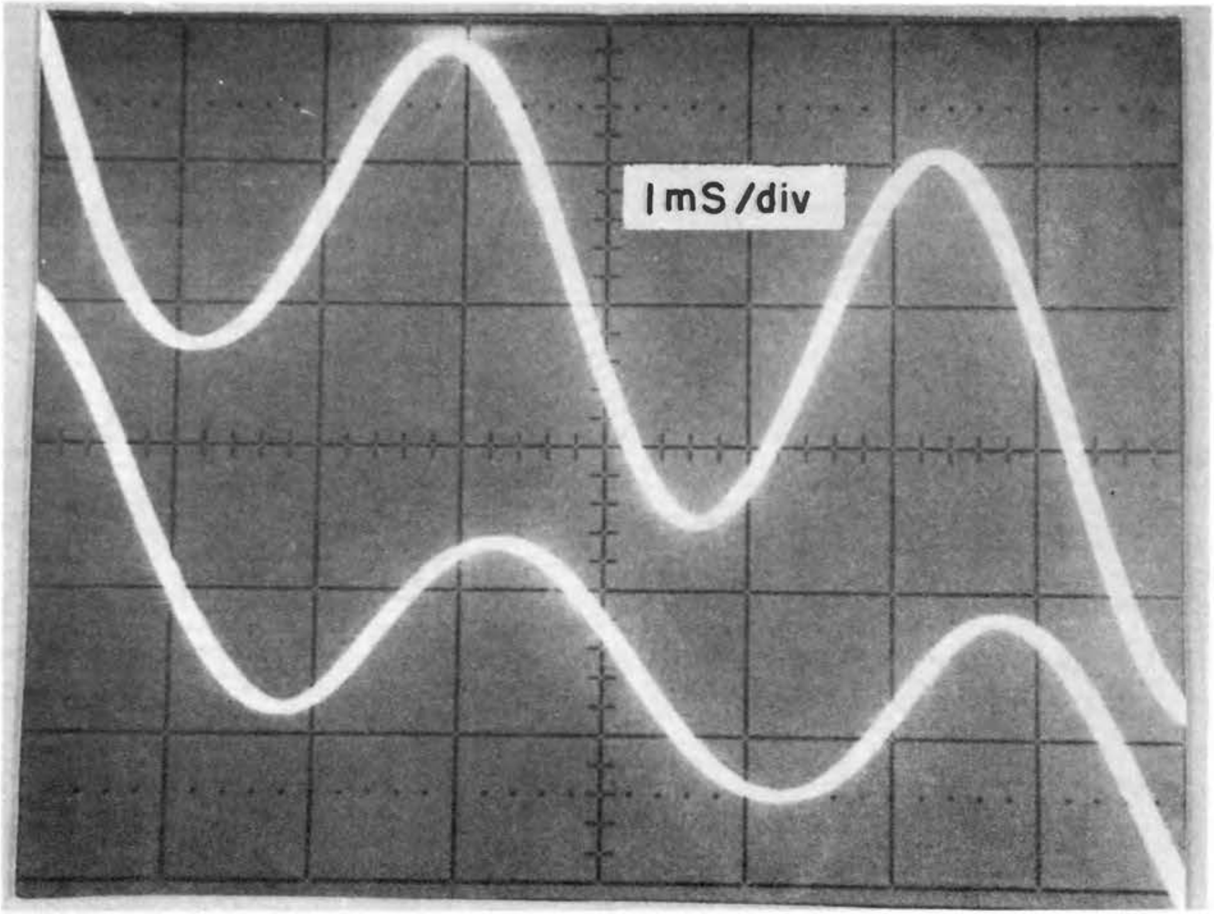
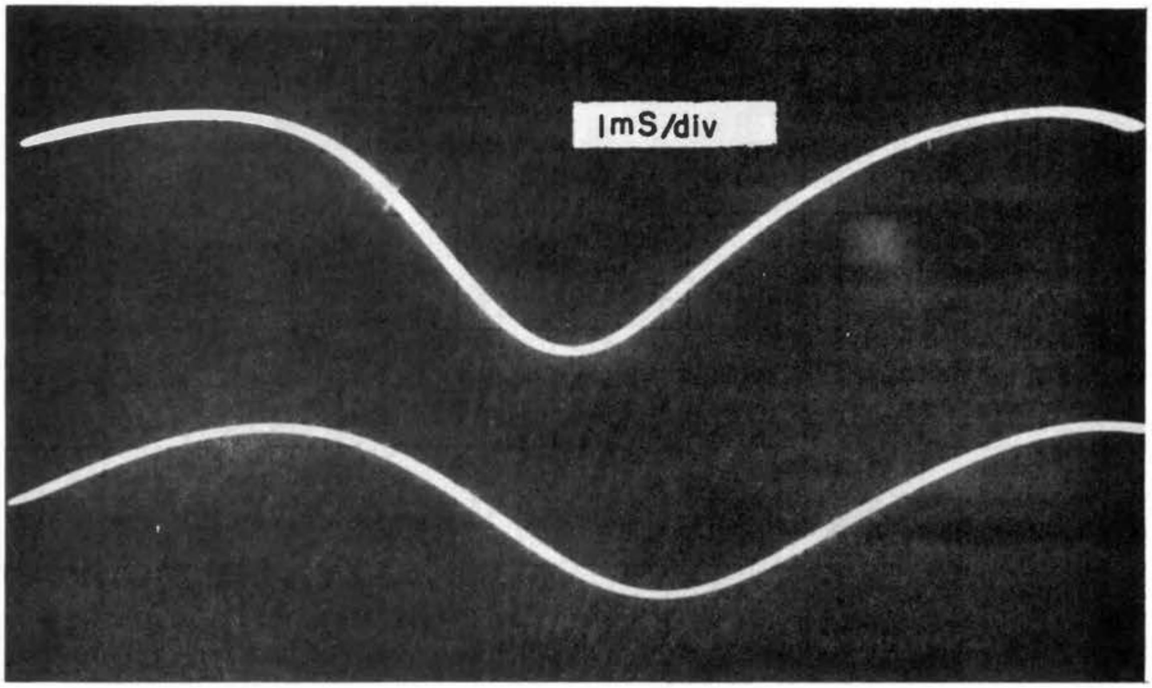
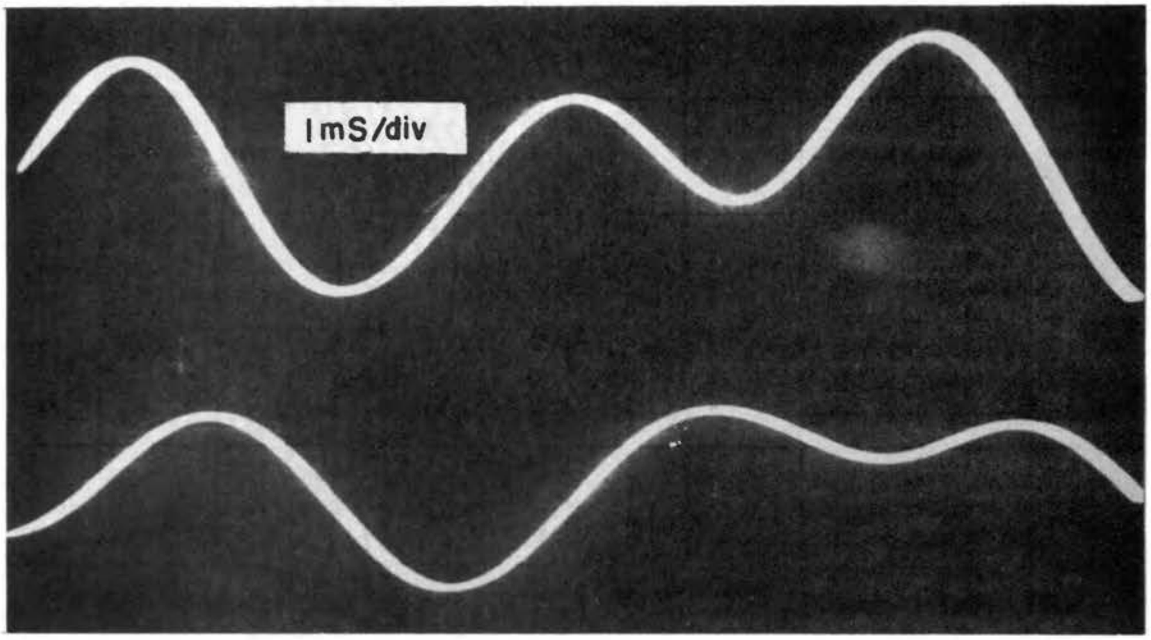


Figure 14. Example of the Signal Used to Determine the Acoustic Velocity in the Fluid



a) % AE = 0 High Pressure Side



b) % AE = 0.3 Low Pressure Side

Figure 15. Examples of the Signal Used to Determine the Acoustic Velocity in the Fluid

CHAPTER V

EMPIRICAL RELATIONSHIPS BETWEEN THE FLUID PARAMETERS OF AN AIR-OIL MIXTURE

The experimental procedure discussed in the previous chapter was implemented to provide empirically based knowledge about the relationships between the acoustic velocity in the fluid (Cs) and the air content in the fluid for a fluid in an operational fluid power system. The fact that the air-oil mixture is in a dynamic state is unique to this study. Other studies of the affect of entrained air content on the bulk modulus of oil have been performed under static conditions.

If cause and effect relationships between fluid power components and systems are to be analyzed with respect to the amount of air in the oil, a dynamic measurement technique which evaluates the amount of air in the oil is necessary. Measurement of the acoustic velocity in the fluid is the dynamic analysis technique that has been evaluated during the project discussed in this report.

It is generally accepted that the results of an experimental study should be compared to the theoretically expected results of the phenomenon being studied. At present, theory that is consistant with what actually occurs in practice concerning the bulk modulus of an air-oil mixture is not available (as discussed in Chapter III).

For the purpose of evaluating the result of the experimental study performed during the project discussed herein the data will be compared to other empirical results that are consistant with the physically allowable limitations of the problem. It is important to note that the data to which the results of this study are to be compared were obtained by trapping a volume of air-oil mixture in a closed volume and compressing it to determine the compressibility of the fluid. This "static" technique is widely used for bulk modulus determination of fluids (27).

Figure 16 presents the results of one experimental study (16). Interestingly enough, the data plotted in Figure 16 has no correlation to the results of the bulk modulus prediction equation plotted in Figure 6, which was presented by the same author. The data has been transposed from the original author's format and has been plotted on a semi-log axis. In this format it is easily approximated by a straight line. The reason for this type of plot will be discussed in the next chapter.

The data from Figure 16 may be used to find the acoustic velocity in the fluid. This is accomplished through the use of Equation 4 and Equation 12, which, when combined, form Equation 37.

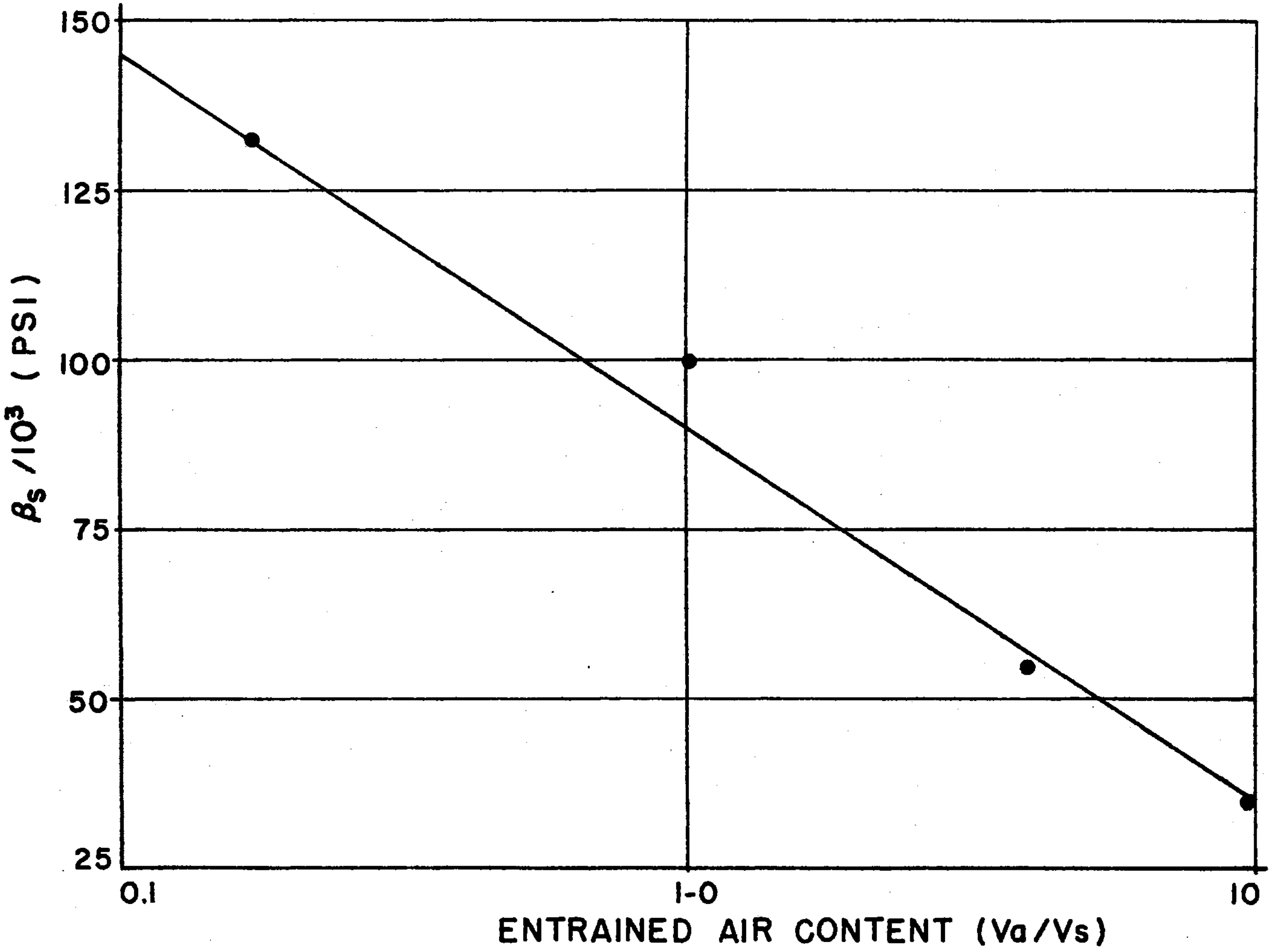


Figure 16. Bulk Modulus of an Air-Oil Mixture for Various Air Contents (Magorien, 1)

$$C_s = \left[\frac{\beta_s g_c}{\rho_s}\right]^{\frac{1}{2}} = \left[\frac{\beta \text{ (Figure 16) } g_c}{\frac{V_a}{V_s}\left(\rho_a - \rho_f\right) + \rho_f}\right]^{\frac{1}{2}} \tag{37}$$

where, $\frac{V_a}{V_s}$ = the abscissa of Figure 16,

β_s = the ordinate of Figure 16,

$\rho_a = .0012 \text{ gm/cc} = .075 \text{ lbm/ft}^3$

$\rho_f = .86 \text{ gm/cc} = 53.69 \text{ lbm/ft.}^3$

Equation 37 was used to generate Figure 17, which shows a derived relationship between the acoustic velocity in a hydraulic fluid and the amount of entrained air present in that fluid. The derived curve is within the physical limits of pure oil (≃5000 ft/sec), and air at atmospheric pressure (≃1100 ft/sec). It seems reasonable to compare the data obtained during the experimental phase of this project to this curve.

The actual experimental effort undertaken during the project discussed in the report consisted of four separate data runs. Each run was performed according to the procedure outlined in Chapter IV. The amount of entrained air in the measurement portion of the test system was varied by changing the pressure and temperature at the measurement point. The volume of air that was injected into the oil was set such that a range of entrained air content of approximately Va/Vs ≈ 0 to Va/Vs = 0.1 could be obtained by setting the static pressure at the measurement position within the range of 5 psi to 20 psi. The pressure at the measurement position was maintained at a positive

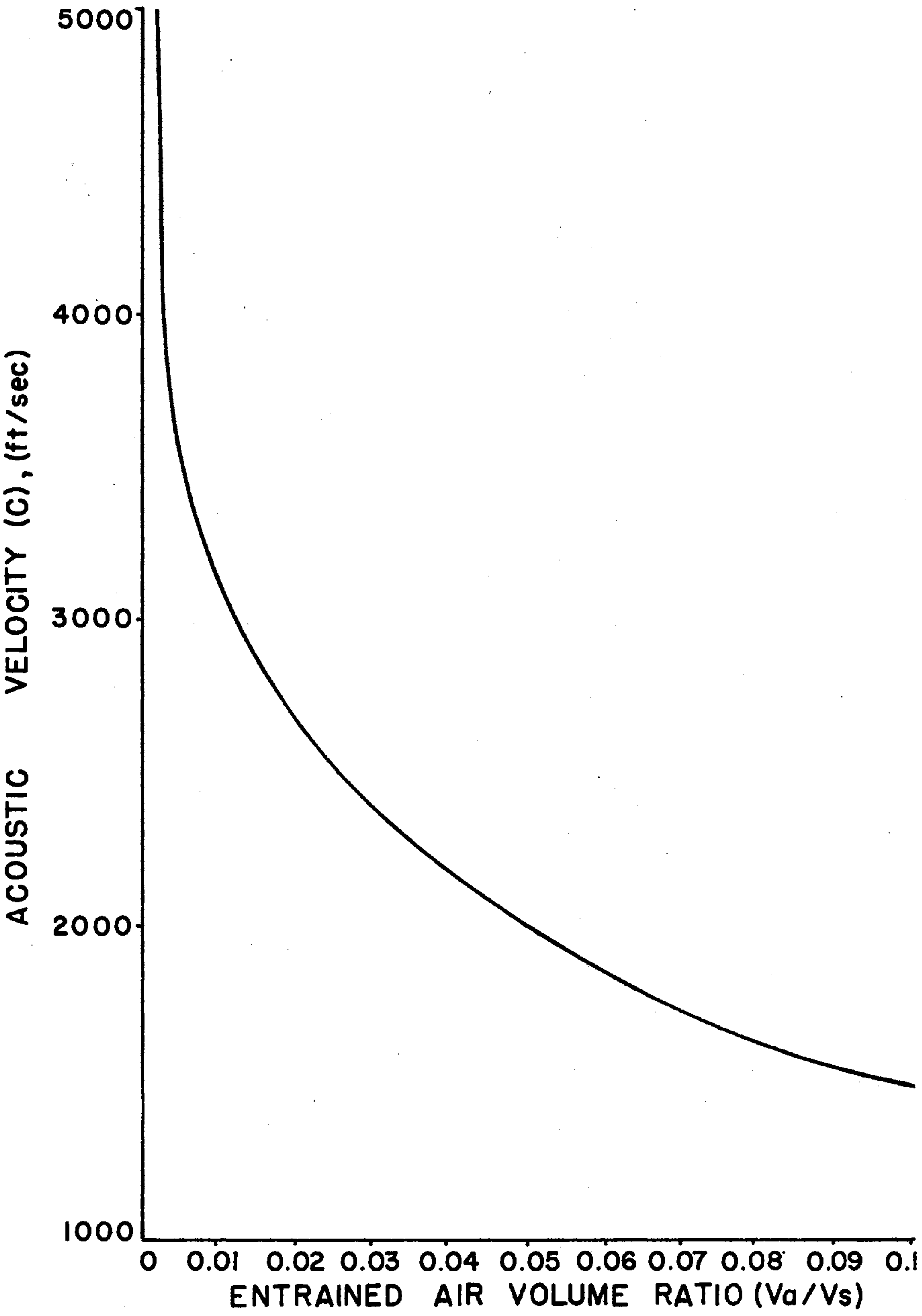


Figure 17. Derived Acoustic Velocity as a Function of Entrained Air

level due to the inability of the pressure transducers to operate at very low pressures or pressures below that of atmospheric. The pressure wave form produced by the test circuit pump became very low in amplitude when the pressure at the inlet was reduced below 5 psi. This fact contributed to the necessity of keeping the pressure above 5 psi during data acquisition.

Measurements of the acoustic velocity were obtained in both the high pressure and low pressure sides of the test system. The high pressure side of the system was maintained at 500 psi. At this pressure the entrained air content was zero for all tests. The measurements in the high pressure side of the system were performed to experimentally verify that the amount of dissolved air does not have an effect on the acoustic velocity in the fluid. For the four different injections of air the acoustic velocity in the high pressure side of the system did not vary appreciably. It did change slightly as the entrained air content on the low pressure side of the system pump became very high (Va/Vs = 0.2). The reduction in acoustic velocity on the high pressure side must be attributed to the time it takes air to re-enter solution with the oil. This re-entry of the air into the solution is not instantaneous. At high entrained air contents on the low pressure side of the pump the amount of air that had to be compressed back into solution was so great that the process was not completed when the fluid passed the high pressure measurement position.

The measurements in the low pressure side of the system were performed for air contents between Va/Vs = 0.0 to Va/Vs = 0.06. Measurements at air contents above Va/Vs = 0.06 were deemed unnecessary due to the qualitative appearance of the oil. The oil looked like "whipped cream" at this air content and all those above it.

Figure 18 presents the experimental results of this project in a linear plot of the sonic velocity in the fluid with respect to the entrained air content. Each of the points on the graph is a mean level computed from six independent measurements of the sonic velocity in the fluid. The value of each individual measurement may be found in Table II, Appendix E. The shape of the curve in Figure 18 appears to be similar to that of the derived curve shown in Figure 17. Figure 19 is a plot of the two curves on a semi-logarithmic axis. The data was plotted in this manner in an attempt to find an axis on which the data could be approximated by a straight line. The curves in Figure 19 are definately similar although distinctly non-lineal.

The experimental data is plotted on a log-log coordinate system in Figure 20. Again, the points on the graph are mean levels of the six measurements obtained at the eight entrained air levels shown. The straight line in the figure is a least square regression on the data. An equation for the line is:

$$C\ (\text{ft/sec}) = 2900\ (\%\,Ae)^{-.2476} \quad . \tag{38}$$

The average error of the experimental data from the regression line is 5.3%. The average error of the derived curve (Figure 17) from

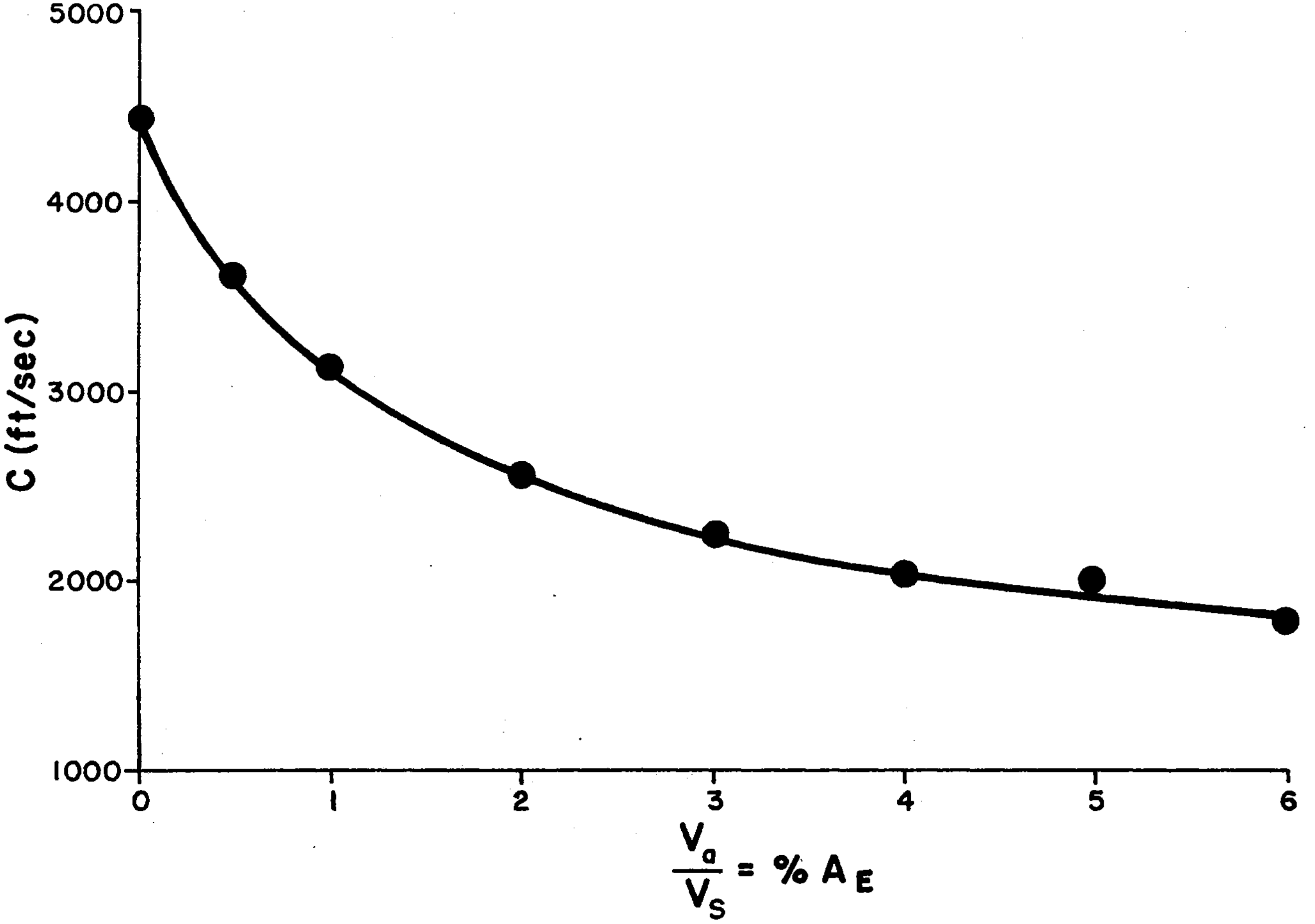


Figure 18. Sonic Velocity vs Fluid Air Content. Mean of Six Measurements Shown by Point at Each Entrained Air Level.

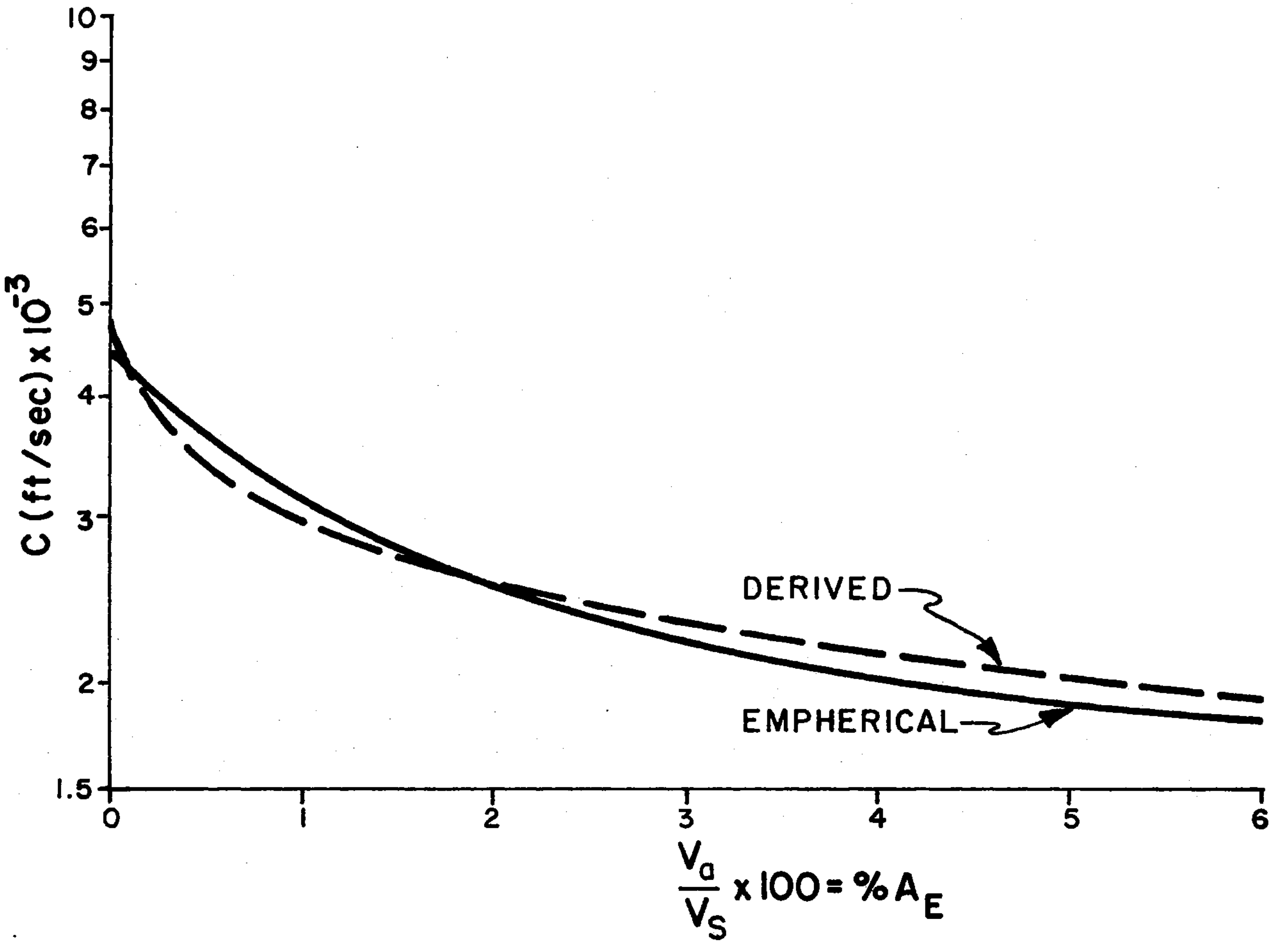


Figure 19. Comparison of Experimental and Derived Curves for Sonic Velocity with Respect to Air Content

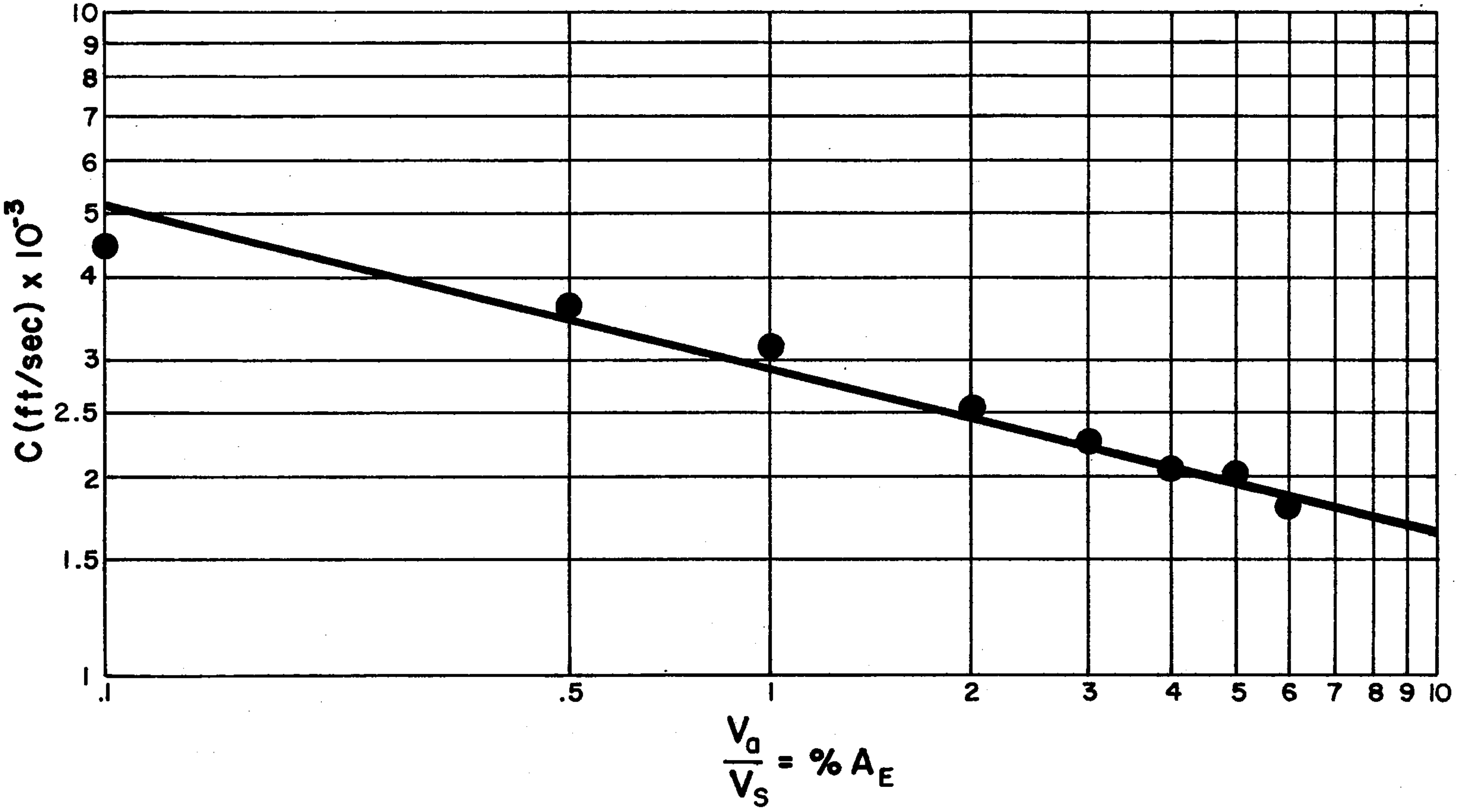


Figure 20. Least Square Regression on Sonic Velocity Data Average Error-5.3%

the regression line in Figure 19 is 4.3%. This small error indicates that the two curves, empirical and derived, are essentially the same.

Figure 21 shows the standard deviation of the measurements at each entrained air level. The standard deviation increases as the entrained air level increases from Va/Vs = 0.00 to Va/Vs = 0.02. The deviation remains relatively constant for any further increase in air content. This increase in the deviation of measurements must be attributed to the increasingly more inhomogeneous fluid as the air content is increased. The fluid remains visually homogeneous below approximately Va/Vs = 0.02. Above this entrained air level large bubbles begin to form, causing the fluid to be more inhomogeneous. The importance of homogeneity in the working fluid cannot be over emphasized (27). Preliminary data taken during the initial phases of this project illustrated the need for properly mixed fluid. No correlation could be established between the entrained air content and the sonic velocity in the fluid due to variation in the data. The technique used to get a homogeneous mixture will be discussed in the next chapter.

The standard deviation of the measurement apparatus may be separated from the deviation of the measurements which contain the error due to the inhomogeneous fluid. The measurement standard deviation is the deviation of the measurements at Va/Vs = 0.00. The error due to the inhomogeneity of the fluid may then be isolated with the equation:

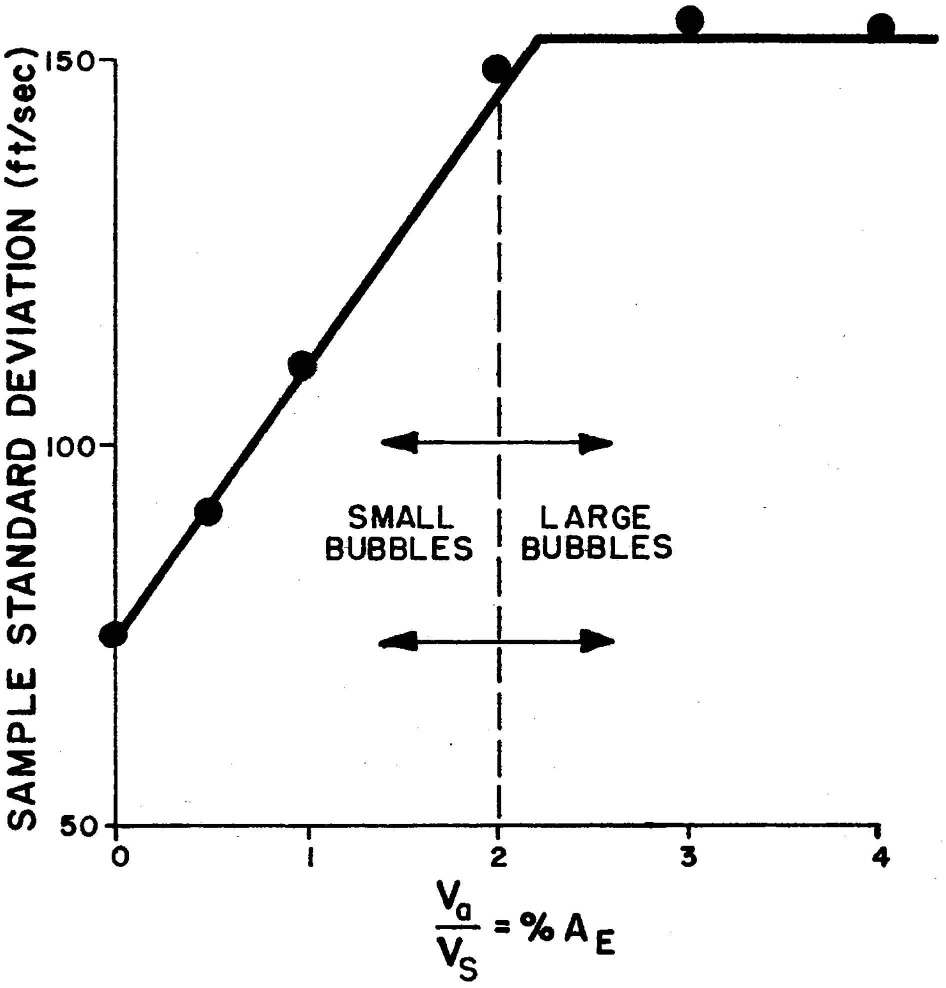


Figure 21. Standard Deviation of Sonic Velocity Measurements vs Fluid Air Content

$$E_h = \left[E_t^2 - E_m^2\right]^{\frac{1}{2}} \qquad (39)$$

This equation may be used to estimate the deviation that can be expected for measurements of the sonic velocity in an air-oil mixture due to the fluid being inhomogeneous.

The next chapter contains a summary of what has been accomplished by the project discussed herein, conclusions concerning the topics discussed and recommendations for further research in the area.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Summary

The project discussed in this report was initiated to more closely define the relationship between two parameters of an air and oil mixture. The two parameters of interest were the acoustic velocity in the fluid, and the amount of air contained in the fluid. The acoustic velocity is related to density and bulk modulus by the equation,

$$\beta = \rho c^2 \tag{40}$$

Equation 40 is important because it presents a relationship between three fluid parameters that are dependent on the amount of the air in the fluid. A relationship between the acoustic velocity in the fluid and the entrained air content was derived through the use of Equation 40. A test system was designed and constructed in which an air-oil mixture with a known ratio of air to oil could be maintained. The acoustic velocity in the fluid was found by measuring the time it took a pressure wave to propagate a known distance in the medium. The acoustic velocity was measured in air-oil mixtures which contained entrained air contents as high as 6% by volume.

The qualitative appearance of the oil was noted during the testing through the use of a sight tube in the low pressure test section. The easily attained visual recognition of entrained air content provides a method of estimating the amount of air in a system. This "estimation technique" and a proposed method of comparing the amount of air in different systems are found in Appendix C.

To the knowledge of this author the "visual technique" discovered during this project provides the most promising field measurement method for the determination of the amount of air in oil that has been proposed to this date. The use of a sight tube in the system flow loop provided the information necessary to obtain consistant results during the measurement of the sonic velocity in the fluid. By studying the fluid in the sight tube it was noted that a stream of bubbles formed at the top of the line. If measurements of the acoustic velocity in a fluid of known consistency are to be made the measurement transducers cannot be located in this stream of bubbles. The transducers were positioned approximately 100° from the vertical axis to insure that they were in the fluid and not in the bubble stream.

Homogeneity of the fluid has been repeatedly emphasized as a necessity during the measurement of the sonic velocity of an air-oil mixture. Wallis (27) discusses the variations of sonic velocity in fluids that are homogeneous and inhomogeneous. Unfortunately, the equation that he presents is for the limiting condition of a fluid-gas interface (non-homogeneous) and homogeneous mixture. The actual conditions that were present in the test section of the system used during this project are somewhere between these limiting conditions. The mixture was formed in a homogeneous state by forcing all of the air injected into the flow loop into solution before reducing the pressure in the test section to the predetermined value that produced a known entrained air level. This procedure resulted in the air expanding from the solution to form a homogeneous mixture of small air bubbles in the oil. Each time the entrained air level was changed the pressure was increased to force the air back into solution, then lowered to allow the air to expand to form bubbles in an evenly distributed manner.

Conclusions

Measurement of the acoustic velocity in an air-oil mixture can provide an accurate indication of the entrained air content of hydraulic oil.

The availability of a method to measure the acoustic velocity in an air-oil mixture when coupled with a theoretical knowledge of variations of the density of a fluid with the introduction of entrained air provides a basis for measuring the apparent bulk modulus between two points in a fluid power system.

It was determined during this investigation that there did not exist a technique by which the bulk modulus of an air-oil mixture could be estimated that produced results which were physically allowable. An empirically derived equation for predicting the bulk modulus with respect to the entrained air content is presented in Equation 41.

$$\beta = -36,500 \ -62,500 \ \log_{10} (Va/Vs) \tag{41}$$

This equation provides the only relationship between the bulk modulus in a fluid containing air and the amount of air contained in the fluid known to this author.

The amount of air in the oil of a system may be estimated by visual identification of the Va/Vs = 0.01 (1% entrained air) level. As mentioned previously in this chapter, a discussion of this estimation technique may be found in Appendix C.

Recommendations

The project discussed in this report has set a foundation for further study into three basic areas of engineering knowledge.

First, it is necessary to more rigorously define the effect of air in hydraulic fluids on the fluid properties.

Second, the measurement of fluid density as an indication of the amount of entrained air present should be considered during any air-oil mixture investigations subsequent to the one reported here.

Third, the accuracy that may be attained through the use of visual aeration level estimation should be determined prior to the acceptance of its use by industry in general as a means by which to rank order the air level of systems.

If sonic velocity measurement is to be used to determine the air content in a fluid of an operating hydraulic system with more accuracy, two modofications should be made to the existing measurement system. The number of samples used to compute the sonic velocity must be increased, and the homogeneity of the fluid must be insured through the use of a turbulence inducing device upstream of the measurement position and screens upstream of the measurement positions to minimize the bubble size of the air in the fluid.

SELECTED BIBLIOGRAPHY

(1) Baldwin, R. R. & Daniels. "The Solubility of Gasses in Lubricating Oils & Fuels." The Journal of the Institute of Petroleum, Volume 39 (1953), 187-203.

(2) Beckwith, T. G. and Buck, N. L. Mechanical Measurements. Massachusetts: Addison-Wesley, 1969.

(3) Davis, D. S. Nomography and Empirical Equations. New York: Reinhold, 1962.

(4) Doebelin E. O. Measurement Systems: Application and Design. New York: McGraw-Hill, 1966.

(5) Florscheutz, L. W. and Chad, B. T. "On the Mechanics of Vapor Bubble Collapse." Journal of Heat Transfer, May, 1965, 209-220.

(6) Hayward, A. T. J. "How to Avoid Aeriation in Hydraulic Circuits." Hydraulics & Pneumatics, November, 1963, 78-83.

(7) Hayward, A. T. J. "Air Bubbles in Oil - Their Effect on Viscosity and Compressibility." Proceedings of the 18th National Conference on Industrial Hydraulics, Volume 16, (1962), 68 - 104.

(8) Hickling, R. "Some Physical Effects of Cavity Collapse in Liquids." Journal of Basic Engineering, March, 1966, 229-235.

(9) Holl. J. W. "An Effect of Air Content on the Occurrence of Cavitation." Journal of Basic Engineering, December, 1960, 941-946.

(10) Knapp, R. T., Daily, J. W. and Hammitt, F. G. Cavitation. New York: John Wiley and Sons, 1962.

(11) Levens, A.S. Nomography, California: Fearow, 1971.

(12) Livesey, R. M. and Ettinger, M. H. "Separator Deareates Oil, Stops Shimmy on F-104 Nose Wheel." Hydraulics and Pneumatics, October, 1967, 149-151.

(13) Mackenzie, W. E. and Smith, J. "Measuring Air Solubility in Hydraulic Fluid." Hydraulics and Pneumatics, August, 1960, 80.

(14) Magorien, V. G. "Techniques for Measuring and Removing Air from Hydraulic Control Systems." Proceedings of the National Conference on Fluid Power, Volume XX (1966), 203-210.

(15) Magorien, V. G. "Effects of Air on Hydraulic Systems." Hydraulics and Pneumatics, October, 1967, 128.

(16) Magorien, V. G. "How Hydraulic Fluids Generate Air." Hydraulics and Pneumatics, June, 1968, 104-108.

(17) Magorien, V. G. "What is Bulk Modulus and When is it Important?" Hydraulics and Pneumatics, November, 1969, 98-101.

(18) Mark, M. Thermodynamics. New Jersey: Prentice-Hall, 1967.

(19) Miller, I. and Fruend, J. E. Probability and Statistics for Engineers. New Jersey: Prentice-Hall, 1965.

(20) N. E. L. Report, National Engineering Report. Number 75. Great Britain: National Engineering Laboratory, January, 1963.

(21) Rendell, D. and Allen, G. R. "The Effect on the Reversibility of a Hydraulic Mechanism of Variations in the Bulk Modulus of a Fluid." Aircraft Engineering, November, 1951, 337-338.

(22) Schweitzer, P. H. and Szebehely, V. G. "Gas Evolution in Liquids and Cavitation." Journal of Applied Physics, Volume 21 (December, 1950), 1219-1224.

(23) Shutler, N. D. and Mesler, R. B. "A Photographic Study of the Dynamics and Damage Capabilities of Bubbles Collapsing near Solid Boundaries." Journal of Basic Engineering, June, 1965, 551-557.

(24) Tourret, R. and White, N. "Aeration and Foaming in Lubricating Oil Systems." Aircraft Engineering, May, 1952, 122-137.

(25) Van Wylen, G. J. and Sonntag, R. E. Fundamentals of Classical Thermodynamics. New York: John Wiley and Sons, 1965.

(26) Veraar, R. "Cleanliness is Key to Good Hydraulic Maintenance." Hydraulics and Pneumatics. November, 1971, 68-70.

(27) Wallis, G. B. One Dimensional Two-Phase Flow. New York: McGraw-Hill, 1969.

(28) White, J. "Bulk Modulus Measurement." Basic Fluid Power Research Program Annual Report, Number 5, General Research, Section 71-1, (July, 1971), 115-140.

APPENDIX A

SYSTEM DESIGN

The data presented in this report were obtained in the OSU-FPRC Acoustics Laboratory. Some unique modifications were added to the existing fluid power system, which made the experimental effort discussed in this report feasible. These innovations and the physical make-up of the remainder of the fluid power system will be discussed in detail in this appendix.

A schematic of the test system is shown in Figure 22. The test system is hydrostatically coupled to a two-hundred horsepower dynamometer. The drive system is shown schematically in Figure 23.

The fluid conditioning circuit shown in Figure 22 has been specifically designed to produce and maintain a precise air-oil mixture. A special air evacuation reservoir was designed to remove both dissolved and entrained air from the oil. Dissolved air contents below 0.5% by volume have been easily attained.

Determination of the dissolved air content after the oil was evacuated is discussed in Appendix C.

A pre-determined air-oil mixture is produced by injecting a known volume of air into a known volume of oil (ie., the volume of the flow loop). Injection of air into the oil is accomplished through the use of a chamber designed specifically for that purpose. The injection chamber consists of a known volume which may be isolated from the system's flow loop. The volume of air that is injected into the oil may be varied by altering the air pressure over a range from -25 inches of mercury to 100 psi. A temperature probe is located in the injection

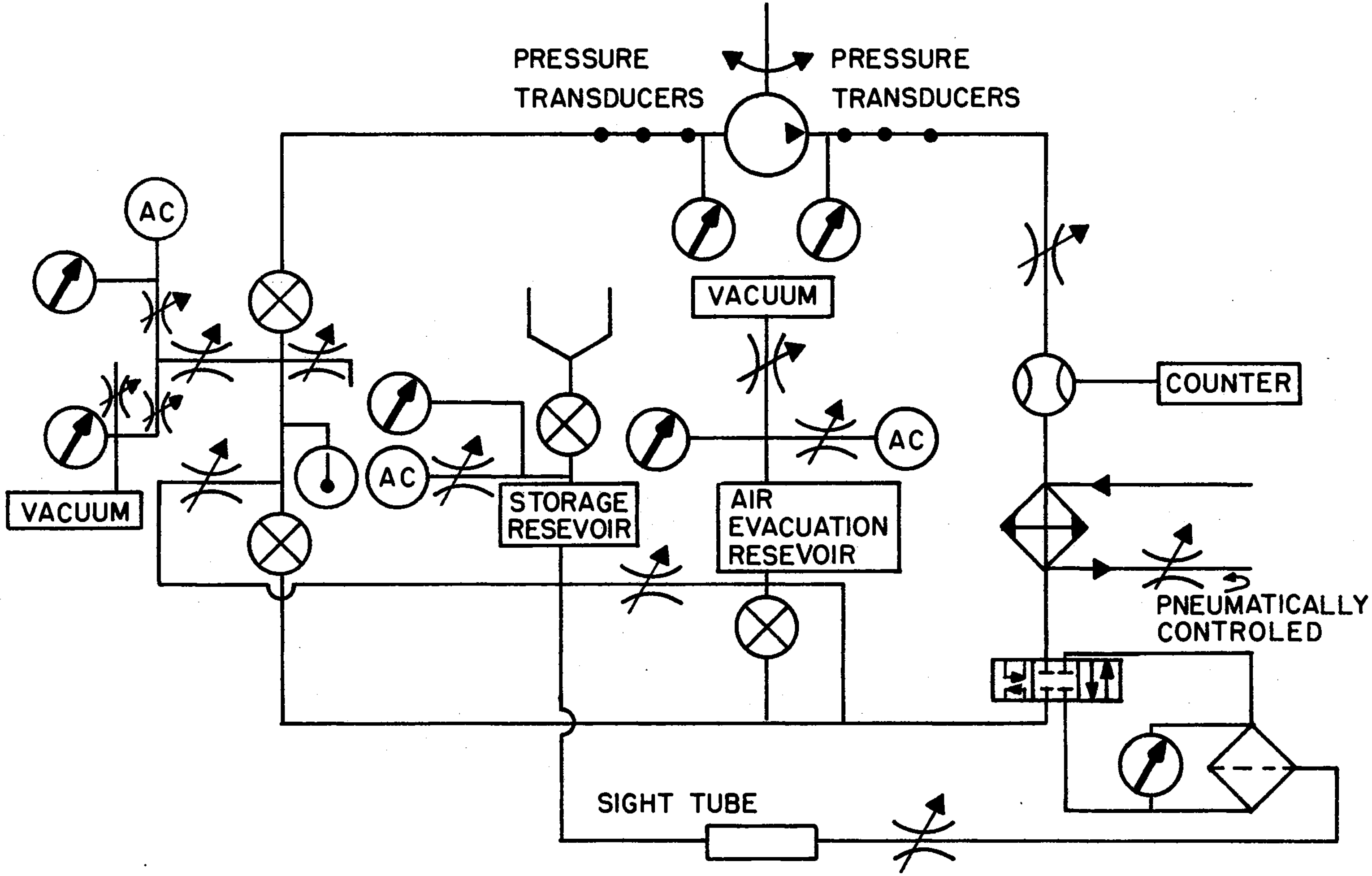


Figure 22. Test System Schematic

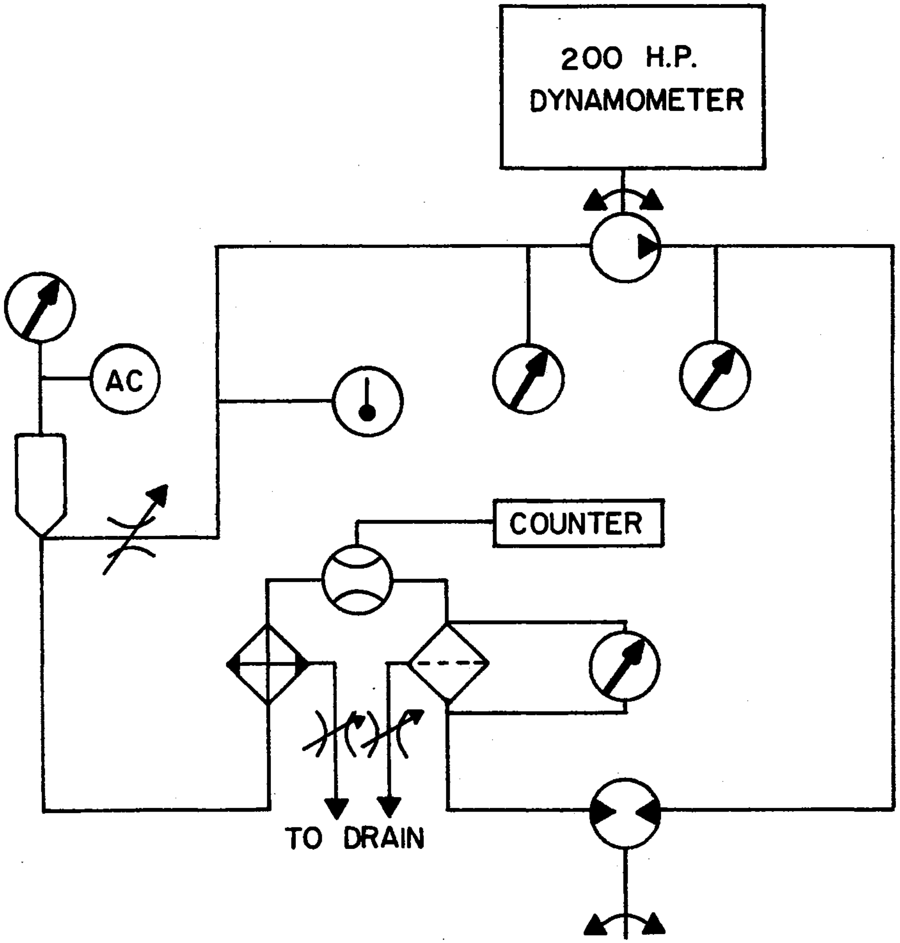


Figure 23. Drive System Schematic

chamber to allow the air temperature to be measured prior to injection into the oil.

APPENDIX B

VOLUME DETERMINATION

Determination of the volume of the air injection chamber and the system's flow loop are critical to the accuracy of data presented in this report. Two methods were used to measure the necessary volumes. The air injection chamber was filled with MIL-2104 hydraulic fluid and evacuated into a graduated cylinder to determine its volume (Vic). The accuracy of this measurement is estimated to be better than 0.25%. The injection chamber volume was found to be:

$$Vic = .546 \text{ gal.}$$

Measurement of the volume of the flow loop was performed in two steps. The first step included the determination of the volume of the external pressure vessel (Vpv). This volume was found in the same manner as the injection chamber and is 7.85 gallons.

The flow loop volume was evaluated by connecting the pressurized pressure vessel to the system and expanding the compressed air to equalibrium into the measurement system. The system volume was then computed using the following equation.

$$P_1 \, Vpv = P_2 \, (Vpv + Vs) \tag{42}$$

where, Vs is the system volume.

The preceeding equation is valid for a perfect gas, with constant specific heats, during an isentropic process. All of these assumptions are correct and valid for air at the pressures and temperatures used during the calculations discussed in this appendix. To insure that the expansion process was isentropic (ie., reversible and adiabatic) the equalibrium pressure of the pressure vessel and system was measured immediately after equalibrium was attained to minimize the effects of heat transfer into the gas.

Table I presents the results of the system volume determination.

TABLE I

SYSTEM VOLUME DETERMINATION

Parameters	Measurement Number			
	1	2	3	4
P_1	104	90	80	78
P_2	40	35	31	30
V_s	12.56	12.33	12.41	12.56

The average system volume for the four measurements presented in Table I was used as the volume of the system for further computations.

The volume of the flow loop (Vfl) was finally determined by subtracting the volume of the branch lines (Vbl) from the empirically derived system volume. The branch line volume was determined by measurement of the physical dimensions of all lines connected to the flow loop that do not function as flow paths. The branch line volume was determined to be 3.53 gallons. The volume of the flow loop, hence the volume of oil which must be mixed with a given volume of air to obtain a known air-oil mixture, was found to be:

$$Vfl = V_s - Vbl = 12.47 - 3.53 = 8.94 \text{ gal.} \qquad (43)$$

The accuracy of the measurement of the volume of the flow loop is dependent upon two sources of error. The first is the error in the pressure gauge used to measure P_1 and P_2, and the second is the least division error incurred during the measurement of the branch line volume. The least division error was estimated to be less than 1% and was neglected due to the 2% error present in the pressure gauge. A calibration of the gauge used during the volume determination phase of the project presented in this report is shown in Figure 24. The calibration was performed with a 5 psi increment dead-weight tester.

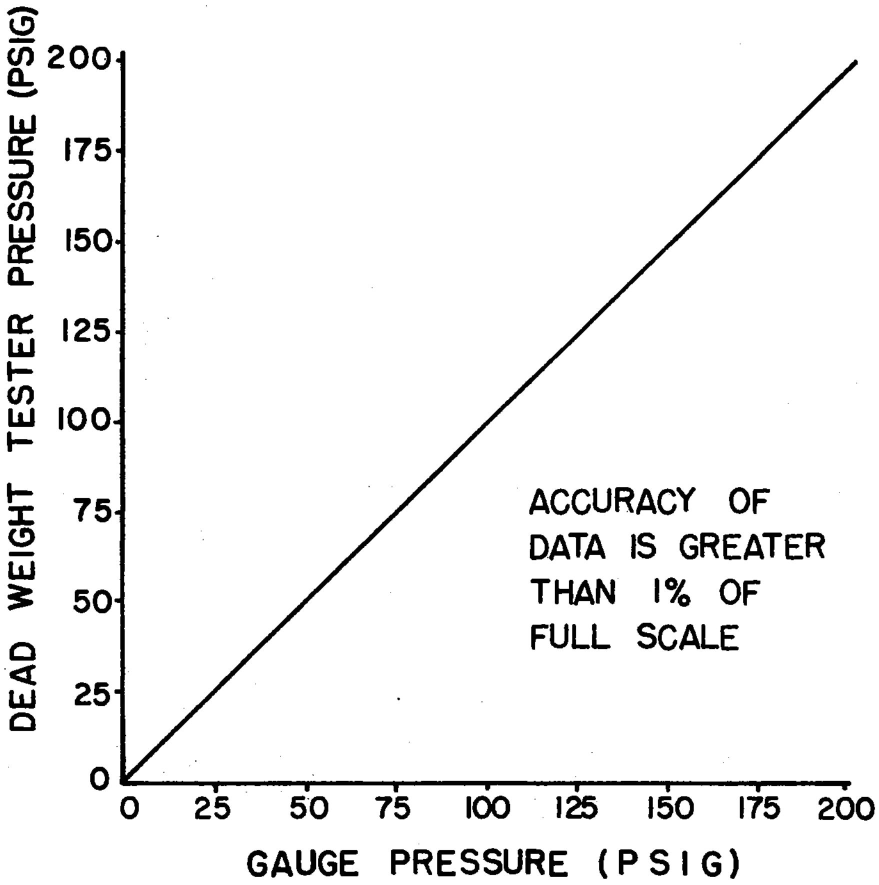


Figure 24. Calibration of Pressure Gauge Used During System Volume Determination

APPENDIX C

FIELD TEST FOR AIR CONTENT

It has become evident during the research performed for the project discussed in this report that a method for comparing the amount of air in the hydraulic oil of different systems is unavailable to the industrial engineer. It is for that reason that a proposed technique which may be used to compare the amount of air in the oil for different systems is presented in this appendix.

The method consists of determining the total volume of air in a known volume of oil, then finding the volume that the total volume of air would occupy at standard temperature and pressure (20°C, 760 mm of mercury), and dividing the volume of air at standard condition by the known volume of oil from step one. The resultant number will be referred to as the "aeriation level".

The total volume of air per unit volume of oil is the entrained air volume ratio (Va/Vs) at a given pressure (Ps) and temperature (Ts) plus the dissolved air volume ratio (Vd/Vf). The dissolved air volume ratio may be determined for any temperature from Figure 12 and Figure 13. The "aeriation level" may then be computed through the use of Equation 44.

$$\frac{Vstp}{Vf} = \frac{PsVt}{Ts}\,\frac{Tstp}{Pstp}\,\frac{1}{Vf} \tag{44}$$

The "aeriation level" is the total volume of air at standard temperature and pressure per unit volume of oil that is present in a given system containing hydraulic oil.

The aeriation level in a system may be estimated by a simple procedure. The presence of entrained air in the hydraulic fluid is easily recognized visually. Small bubbles begin to form at approximately Va/Vs = 0.01. When the amount of entrained air is increased to approximately Va/Vs = 0.02 the oil begins to appear cloudy. There is a range of entrained air content from Va/Vs = 0.00 to Va/Vs = 0.02 when only small bubbles are present in the oil. This fact may be used to estimate the aeriation level of a system. If the inexpensive device shown in Figure 25 is put at the lowest pressure point in a system (usually the suction side of the system pump), the needle value may be adjusted to achieve small bubbles of air in the oil passing through the right tube. At the conditions of pressure and temperature displayed on the gauge of the test apparatus there exists an entrained air volume ratio of Va/Vs = 0.01. The dissolved air ratio is evaluated, as previously discussed, from Figures 12 and 13. The aeriation level in the system may then be calculated from Equation 44.

This method of measuring the amount of air in an operational hydraulic system is less accurate than the other techniques discussed in this text due to its reliance on visual determination of an entrained air volume ratio of Va/Vs = 0.01. The visual analysis technique is, however, far less expensive to implement than other more accurate methods.

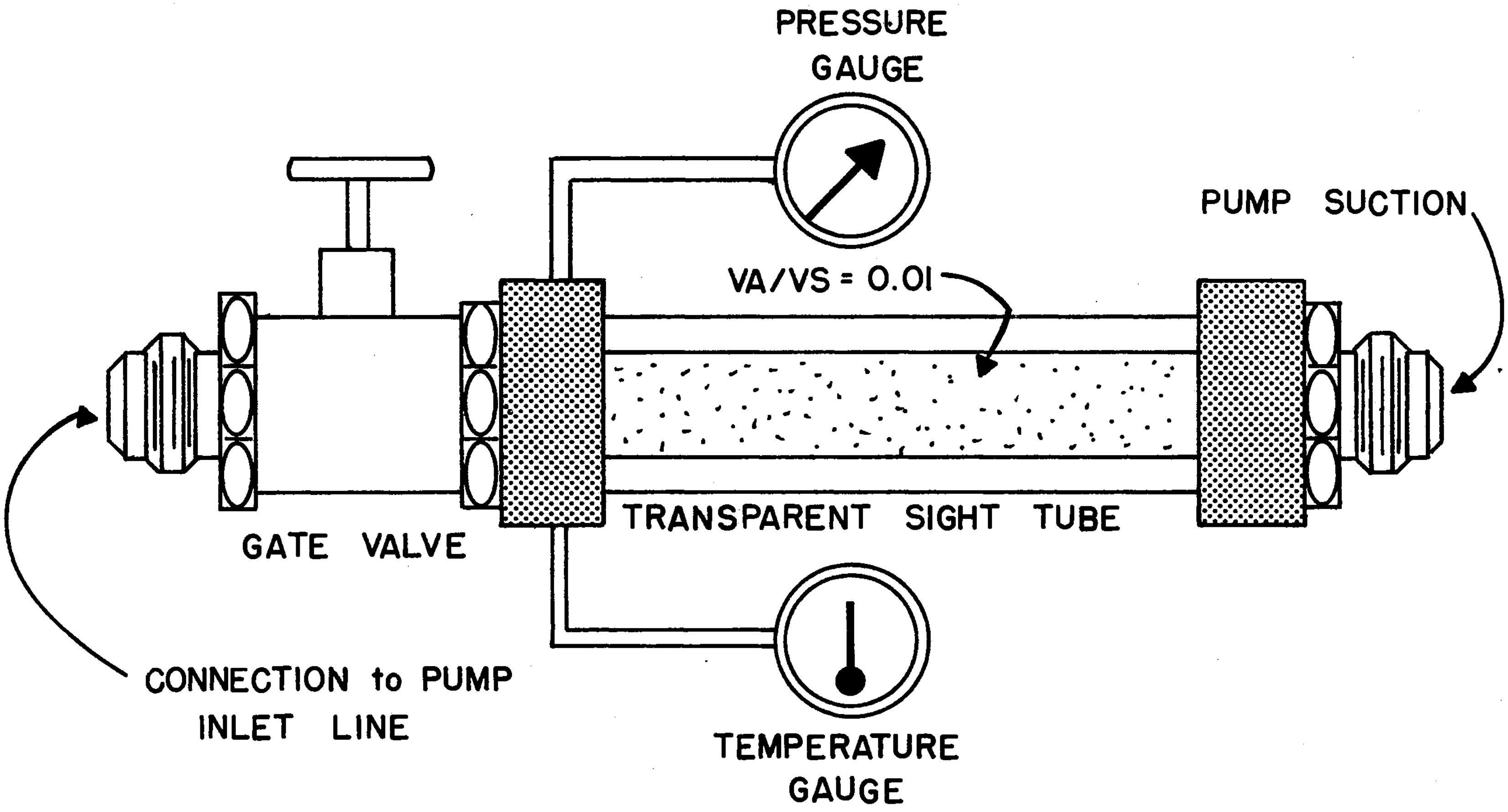


Figure 25. Aeriation Level Estimation Device

APPENDIX D

INSTRUMENTATION

The following list of instrumentation was used during the experimental portion of the project discussed in this report.

Instrument	Manufacturer	Type	S/N
Pressure Transducer	P. C. B. Piezotronics	118A0Z	646
"	"	"	647
"	"	"	648
"	"	"	649
"	"	"	650
"	"	"	651
Six Channel Power Supply	"	438A0Z	274
Pressure Amplifier	"	402A	1109
"	"	"	1110
"	"	"	1111
"	"	"	1118
"	"	"	1119
"	"	"	1120
Oscilloscope	Hewlett Packard	1703A	1232A00781
Filter	Multimetrics	AF-120	S124501

APPENDIX E

DATA

The data presented in this appendix are the result of the application of the experimental procedure outlined in the text of this report. Four separate data runs were performed. The data is presented in a reduced tabular form. All measurements of the acoustic velocity have been reduced from their raw form as read from the oscilloscope. All other values presented in Table II are either known or calculated from the analytical procedures discussed previously.

TABLE II

ACOUSTIC VELOCITY vs AIR CONTENT DATA

			Measurement Number @ Indicated % Ae					
%Ae	$\bar{x}$	σ	1	2	3	4	5	6
0	4380	75	4495	4444	4301	4347	4347	4347
0	4478	80	4444	4395	4395	4597	4495	4545
.5	3621	91	3571	3603	3603	3703	3508	3738
1	3143	110	3175	3076	3125	3333	3100	3053
2	2542	149	2424	2380	2631	2547	2515	2758
3	2274	156	2247	2298	2173	2501	2500	2325
4	2050	154	2150	2234	2000	1843	2061	2020
5	2019	101	2198	1941	2041	2000	1904	2030
6	1781	144	1746	1716	1835	1606	1970	1818

VITA

Larry Roger Elliott

Candidate for the Degree of

Master of Science

Thesis: DYNAMIC DETERMINATION OF THE AIR CONTENT IN HIGH PRESSURE FLUID SYSTEMS THROUGH SONIC VELOCITY MEASUREMENT

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Dallas, Texas, February 2, 1947, the son of John W. and E. Francis Elliott.

Education: Graduated from Waynesboro High School, Waynesboro, Pennsylvania, in May, 1965; received Bachelor of Science degree in Mechanical Engineering from Oklahoma State University in 1972.

Professional Experience: Employed: as an undergraduate research assistant from February, 1968, through January, 1971 by the Mechanical and Aerospace Engineering Department of Oklahoma State University to study the pressure fluctuations under the boundary layer on the exterior surface of a glider in subsonic flight; as a graduate research assistant from January, 1971, through January, 1972, by the Basic Fluid Power Research program at the Fluid Power Research Center, Oklahoma State University, studying wear in fluid power systems; as a project engineer for the U.S. Army MERDC sponsored research concerning the noise produced by fluid power systems on Army mobile equipment from January, 1972, through May, 1974, at the Fluid Power Research Center, Oklahoma State University.