Cy/ 36

20p. r

MSFC

MTP-P&VE-S-62-2
April 5, 1962

N64 10104

CODE-1

Cop. auth: NASA

GEORGE C. MARSHALL SPACE FLIGHT CENTER,

6021703

HUNTSVILLE, ALABAMA

(NASA TM X-51071;

# A METHOD FOR PRELIMINARY DETERMINATION OF COMPONENT STIFFNESS REQUIREMENTS FOR GIMBALED ENGINE SYSTEMS

MTP-P; VE-S-62-2)

by

Charles E. Lifer

Apr. 5, 1962 20p refs

OTS PRICE

XEROX $ 1.60 ph

MICROFILM $ 0.80 mf.

OTS: $1.60 ph, $0.80 mf.

NASA

FOR INTERNAL USE ONLY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

RQT 4743

MSFC - Form 523 (Rev. November 1960)

GEORGE C. MARSHALL SPACE FLIGHT CENTER

MTP-P&VE-S-62-2

# A METHOD FOR PRELIMINARY DETERMINATION OF COMPONENT STIFFNESS REQUIREMENTS FOR GIMBALED ENGINE SYSTEMS

By Charles E. Lifer

ABSTRACT

10104

To facilitate preliminary design of gimbaled engine systems which will meet vibration requirements of hydraulic and electronic controls, this report presents a method for approximate determination of component requirements. The report is intended to show the required relationships between the design frequency, the engine mass and stiffness, the actuation system stiffness, and support structure stiffness. In addition, it will present procedures for determining these component properties.

Since the report is for preliminary study only, and detailed mass distribution and stiffness information will not be available, a single degree of freedom analysis method was chosen. The predicted masses of gimbaled components are assumed to be concentrated at one location. The support structure will be treated as a linear spring. Because of these simplifying assumptions, the results of an analysis with this method must be used conservatively.

It is recommended that, as designs are established and detailed information becomes available, more elaborate analytical techniques which are fitted to the specific design be used for accurate frequency determination.

AUTHOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER

MTP-P&VE-S-62-2

# A METHOD FOR PRELIMINARY DETERMINATION OF COMPONENT STIFFNESS REQUIREMENTS FOR GIMBALED ENGINE SYSTEMS

by

Charles E. Lifer

STRUCTURES BRANCH
PROPULSION AND VEHICLE ENGINEERING DIVISION

## TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

## DEFINITION OF SYMBOLS

| SYMBOL | DEFINITION | UNITS |
|---|---|---|
| $K_R$ | Effective rotational stiffness of entire engine gimbal system | in-lb/radian |
| $K_A$ | Linear stiffness of engine actuator(s) | lb/in |
| $K_V$ | Linear stiffness of vehicle structure at the actuator attach point in the direction of the actuator loading | lb/in |
| $K_E$ | Linear stiffness of the engine structure at the actuator attach point in the direction of the actuator loading | lb/in |
| d | Effective moment arm of the engine actuator(s) about the engine gimbal support | in |
| J | Rotational mass moment of inertia of the engine about its gimbal support | $lb\text{-}in\text{-}sec^2$ |
| $f_n$ | Natural rotational frequency of the engine system | cycles/sec |
| $\ddot{\theta}$ | Angular acceleration of the engine about the gimbal point | $radian/sec^2$ |
| $\dot{\theta}$ | Angular velocity of the engine rotating about the gimbal point | radian/sec |
| $\theta$ | Angular displacement of the engine from its normal position | radian |
| $\omega$ | Circular rotational frequency | radian/sec |
| $K_\Sigma$ | Total effective linear stiffness of system components | lb/in |
| $K_S$ | Structural component of actuator stiffness | lb/in |

Definition of Symbols (Concluded)

| | | |
|---|---|---|
| $K_F$ | Fluid component of actuator stiffness | lb/in |
| $K_O$ | O-ring and seal component of actuator stiffness | lb/in |

GEORGE C. MARSHALL SPACE FLIGHT CENTER

MTP-P&VE-S-62-2

# A METHOD FOR PRELIMINARY DETERMINATION OF COMPONENT STIFFNESS REQUIREMENTS FOR GIMBALED ENGINE SYSTEMS

by Charles E. Lifer

## SUMMARY

This report was compiled to assist in the preliminary design of first stage engine systems and engine support structure to meet gimbal vibration frequency requirements. A method of determining basic component physical properties is developed, and is presented in both mathematical and graphical form. The basic theory of a typical system is developed, and the considerations involved in deriving component stiffnesses are discussed.

Use of the method presented herein will enable the designer to determine, for a particular engine, the required inter-relation between system components (actuator, structure, and engine) in order to meet the minimum gimbal frequency. These values can be used as a guide in the design. It must be noted, however, that the design which is evolved should be subjected to a detailed vibration analysis using multiple degrees of freedom and accurate mass distribution.

## INTRODUCTION

In the design of space vehicle engine gimbal systems and support structures, it is necessary to establish physical requirements for the various components which will cause the first gimbal resonant frequency of the system to occur above a certain limiting frequency, $f_{min}$. This requirement is normally imposed by control system characteristics, and is necessary for stability and control of the vehicle.

The purpose of this report is to describe a method of determining the component stiffnesses which will result in a desired frequency for the system. The report is intended for use in preliminary analysis only; and as the design is developed, a more detailed multiple-degree-of-freedom analysis should be performed. Since this method involves a single degree-of-freedom analysis, the results derived therefrom must be treated as limiting minimum values. (For more complete, multiple-degree-of-freedom methods, the analyst is directed to References 1 and 2).

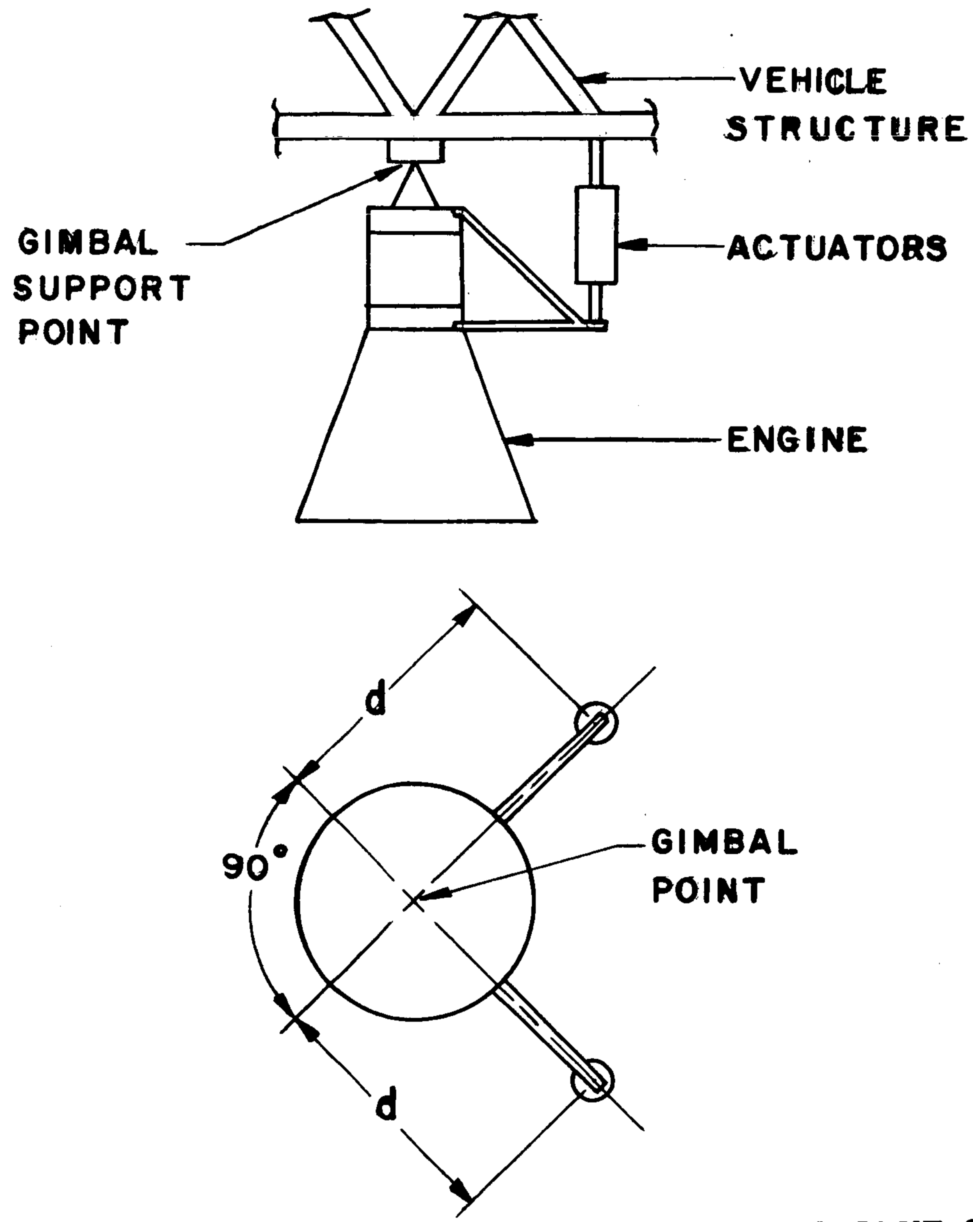
## DEVELOPMENT OF METHOD

A typical gimbaled engine system consists of an engine suspended from the tail section structure by a gimbal block which permits angular displacement of several degrees in any direction. This displacement is controlled (normally) by actuators located at equal distances along mutually perpendicular axes, as shown in FIG 1. Extension or retraction of one or both of the actuators allows any desired displacement to be accomplished, within certain limits.

The dynamic representation of this system is shown in FIG 2, with the system components delineated. The geometry of this system is such that the vibration analysis may be made of gimbal rotation about an axis through one actuator centerline and the gimbal point, thus eliminating that actuator as an effective spring in the system. The same approximate result would be obtained by considering vibration about any other axis through the gimbal point.

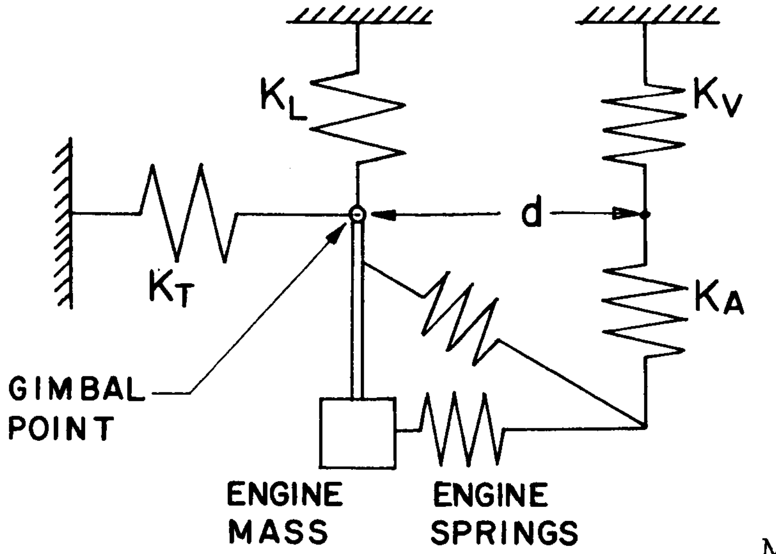
For most vehicle structures, the translational frequency levels involving $K_T$ and $K_L$ (see FIG 2) will be very high in comparison with the gimbal frequency. Also, the gimbal support and the actuators will normally tie into connected structure, and will displace as a unit. For these reasons, the translational spring rates of the gimbal point structure will be considered as infinite. The component stiffnesses of the engine will be lumped, and considered as one effective spring rate, $K_E$, parallel to the actuator line of action. The simplified dynamic system thus obtained is shown in FIG 3.

This system may be simplified further by calculating a single effective linear spring which is equivalent to the three springs in series.



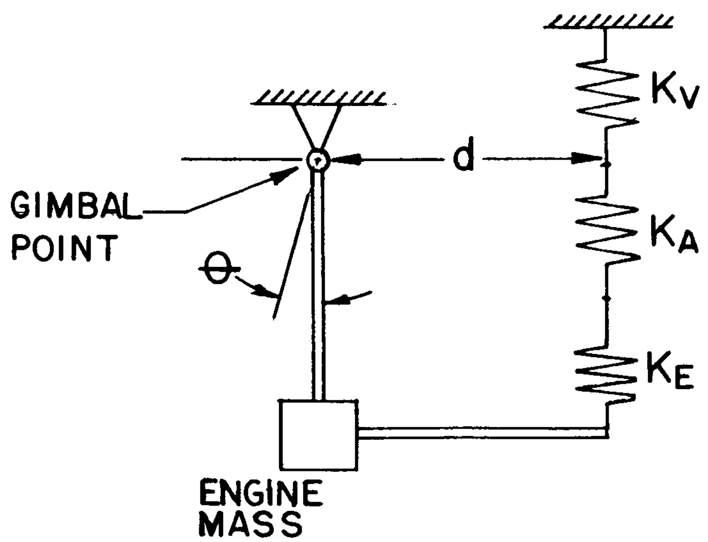

MTP-P&VE-S-62-2

FIGURE 1. TYPICAL GIMBALED ENGINE SYSTEM




MTP-P&VE-S-62-2

FIGURE 2. DYNAMIC REPRESENTATION OF GIMBALED ENGINE SYSTEM




MTP-P&VE-S-62-2

FIGURE 3. SIMPLIFIED DYNAMIC REPRESENTATION OF GIMBALED ENGINE SYSTEM

The equation for such a spring, $K_\Sigma$, is:

$$\frac{1}{K_\Sigma} = \frac{1}{K_V} + \frac{1}{K_A} + \frac{1}{K_E} \tag{1}$$

The rotational spring constant is related to the linear stiffness by the following equation:

$$K_R = K_\Sigma \cdot d^2 \tag{2}$$

The differential equation of free, undamped vibratory motion of this "pendulum" system is:

$$\ddot{\theta} \cdot J + K_R \cdot \theta = 0 \tag{3}$$

Therefore,

$$\ddot{\theta} + \left(\frac{K_R}{J}\right) \cdot \theta = 0 \tag{4}$$

One form of the general solution of this second order differential equation is:

$$\theta = A \cdot \sin \omega t + B \cdot \cos \omega t$$

Substituting this solution into the differential equation, we obtain:

$$\theta \cdot \left(-\omega^2 + \frac{K_R}{J}\right) = 0 \tag{5}$$

Letting $\theta = 0$,

$$\omega^2 = \frac{K_R}{J} \tag{6}$$

Since $\omega = 2\pi f$

$$f = \frac{1}{2\pi} \sqrt{\frac{K_R}{J}} \qquad (7)$$

In the preliminary design of the engine system, the approximate engine inertia and the required frequency will normally be known, so that the following form of the frequency equation will be more useful:

$$K_R = J \cdot \left(2\pi f\right)^2 \qquad (8)$$

With this expression the entire system rotational stiffness may be calculated from the mass properties and frequency requirement.

## GRAPHICAL SOLUTION OF ROTATIONAL STIFFNESS REQUIREMENTS:

A graphical representation of equation 8 $\left[ K_R = J \left(2\pi f\right)^2 \right]$ is given by FIG 4, where nominal values of gimbal resonant frequency (f), rotational inertia (J), and rotational stiffness ($K_R$) are related. This figure may be used for rapid approximation of the stiffness requirement for given values of inertia and frequency. The inertia value is located on the left side of the figure, and the intersection of this value and the desired frequency curve is plotted. The corresponding value of rotational stiffness is located along the top of the figure.

## GRAPHICAL SOLUTION OF LINEAR STIFFNESS REQUIREMENTS:

Rapid determination of the total equivalent linear stiffness ($K_\Sigma$) may be obtained by use of FIG 5, which is a graphical expression of equation 2. The required value of rotational stiffness ($K_R$) is located along the upper margin of the figure, and the intersection of this value and the design moment arm (d) is plotted. The corresponding value of linear stiffness ($K_\Sigma$) is read from the right-hand margin of the figure.

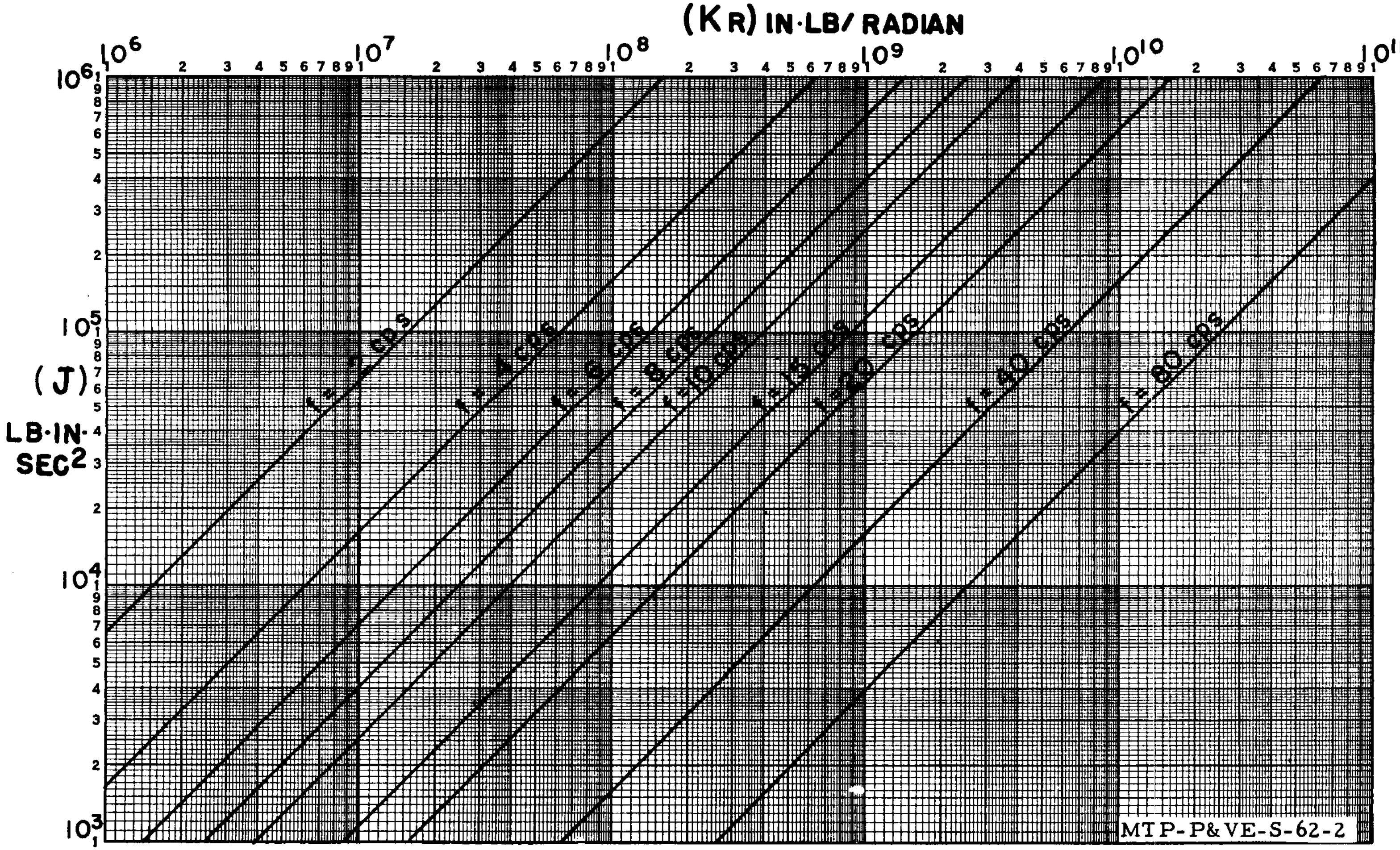



FIGURE 4: RELATIONSHIP BETWEEN SYSTEM ROTATIONAL INERTIA (J), GIMBAL FREQUENCY (f), AND ROTATIONAL STIFFNESS (KR).

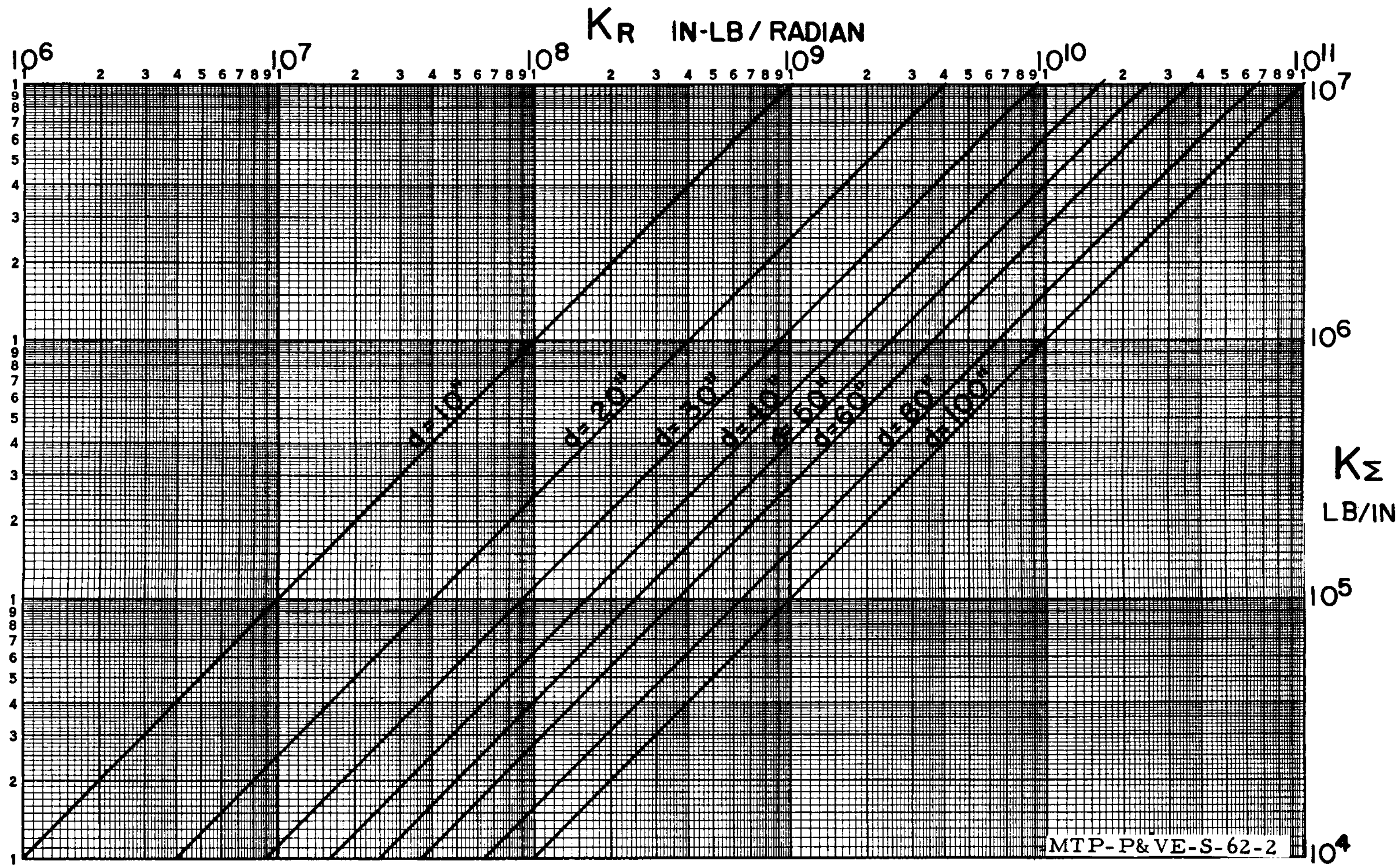



FIGURE 5: RELATIONSHIP BETWEEN SYSTEM ROTATIONAL STIFFNESS ($K_R$), ACTUATOR MOMENT ARM (d), AND LINEAR STIFFNESS, ($K_\Sigma$).

## GRAPHICAL SOLUTION OF COMPONENT LINEAR STIFFNESS REQUIREMENTS:

FIG 6 provides a method for rapid determination of component linear stiffnesses which will result in the required total linear stiffness. The required $K_{\Sigma}$ value is located along the left margin of the figure, and the intersection of this value with the appropriate actuator stiffness curve ($K_A$) is plotted. (Note that the actuator stiffness curves are located in the lower right-hand section of the figure.) From this intersection a vertical line is projected upward to the engine stiffness ($K_E$) curve, and their intersection plotted. From this intersection point the required value of vehicle structural stiffness ($K_V$) may be read along the right margin scale.

## CONSIDERATIONS IN DETERMINING COMPONENT STIFFNESSES:

### Actuator Stiffness, $K_A$

For the usual case of a double-acting hydraulic cylinder actuator, the following must be considered in a prediction of linear stiffness:

(1) Actuator structure stiffness. The combined spring rate of the cylinder walls, piston, and connecting linkage. ($K_S$)

(2) Compressibility of actuator fluid. This is a function of the volume of the entrapped fluid in the cylinder, piston area, operating pressure, and temperature. ($K_F$)

(3) Stiffness of O-ring seals. These are the seals which retain the actuator fluid. ($K_O$)

The combined effect of these variables determines the actuator stiffness, $K_A$, as shown in the equation below:

$$\frac{1}{K_A} = \frac{1}{K_S} + \frac{1}{K_F} + \frac{1}{K_O} \qquad (9)$$

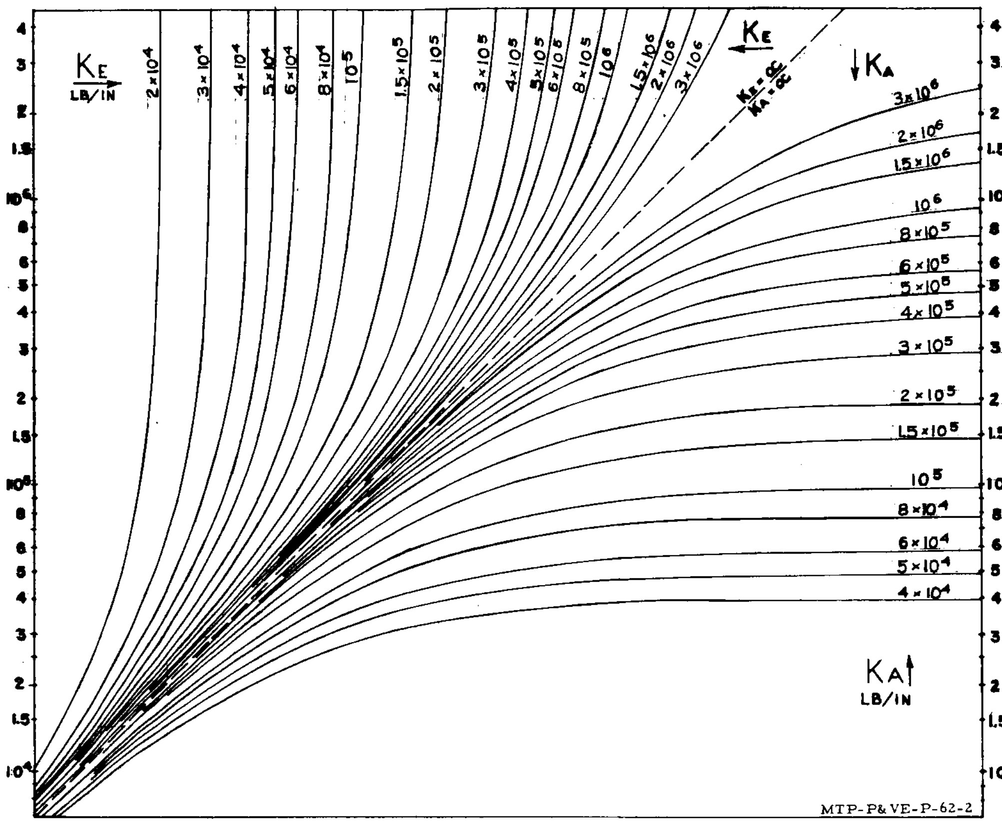



FIGURE 6: PLOT OF TOTAL STIFFNESS VS. COMPONENT STIFFNESSES

## Engine Stiffness, $K_E$

Determination of engine stiffness will depend upon the specific engine design. The method of transferring actuator loads into the engine must be considered. In most cases a laboratory test will be necessary for accurate engine stiffness determination; however, for most designs the following considerations will allow an estimate of engine stiffness:

(1) Attachment structure stiffness, including actuator attach linkage and other structure external to the engine chamber.

(2) Chamber stiffness, which is a function of the manner in which actuator loads are introduced into the engine chamber, bending and ring flexure in the chamber, and local deformations at attach points.

## Vehicle Structure Stiffness, $K_V$

The calculation of vehicle attachment point stiffness is necessarily dependent upon the particular vehicle design. This structure will usually be redundant and the analysis will be complex. The analyst is therefore referred to methods contained in References 3 and 4.

# REFERENCES

1. Harris, C. M. and Crede, C. E., Shock and Vibration Handbook, McGraw-Hill Book Company, New York, 1961.

2. Den Hartog, J. P., Mechanical Vibration, McGraw-Hill Book Company, New York, 1956.

3. Peery, D. J., Aircraft Structures, McGraw-Hill Book Company, New York, 1949.

4. Seely, F. B., and Smith, J. O., Advanced Mechanics of Materials, John Wiley and Sons, New York, 1959.

APPROVAL MTP-P&VE-S-62-2

# A METHOD FOR PRELIMINARY DETERMINATION OF COMPONENT STIFFNESS REQUIREMENTS FOR GIMBALED ENGINE SYSTEMS

By Charles E. Lifer

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

ROBERT L. McCOMAS
Chief, Component Vibration Analysis Unit

N. SHOWERS
Chief, Dynamics Section

G. A. KROLL
Chief, Structures Branch

W. A. MRAZEK
Director, Propulsion and Vehicle Engineering Division

## DISTRIBUTION

| | |
|---|---|
| M-P&VE-DIR | Mr. Mrazek |
| M-P&VE-OEM | Mr. Belew |
| M-P&VE-FD | Mr. Neighbors |
| M-P&VE-S | Mr. Kroll |
| M-P&VE-SA | Mr. Blumrich |
| M-P&VE-SB | Mr. Verble |
| M-P&VE-SS | Mr. Sterett |
| M-P&VE-SD | Mr. Showers |
| M-P&VE-SD | Mr. McComas (6) |
| M-P&VE-SE | Mr. Sawyer |
| M-P&VE-P | Mr. Paul |
| M-P&VE-PL | Mr. Reed |

M-AERO-DIR

M-ASTR
- Mr. Wiesenmaier
- Mr. Wagner
- Mr. Morea
- Mr. Drawe
- Mr. Chubb

M-MS-IP, Mr. Remer
M-MS-IPL (8)
M-P&VE-ADMP
M-PAT
M-MS-H
M-HME-P