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PROGRESS REPORT NO. 4

ON

CALIBRATION OF ANDEROMETERS

Period Ending September 30, 1960

Submitted to:

U.S. DEPARTMENT OF THE NAVY

CHIEF, BUREAU OF SHIPS

WASHINGTON 25, D.C.

RETURN TO PROPELLER, SHAFTING
AND BEARING BRANCH.
CODE 644

Edwin Fink

Olof Gustafsson

U.S. Navy Contract No. NObs-78593
U.S. Navy Serial No. 1734B/250
TR 644-OA

SKF Report L60L024
SKF Code 61021290
SKF Project CR - 01
SKF Reg. 422 3

RESEARCH LABORATORY
SKF INDUSTRIES, INC.
PHILADELPHIA, PA.

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SUMMARY

This report contains a review and recommendations on the following subjects:

1. Study of characteristics of Anderometer pickup and of a more suitable pickup.

2. New loading device for Anderometers.

3. Study of the effect of the spindle assembly on bearing vibration readings.

A program of work for the next reporting period is also given.

The piezo-electric calibration technique presently used at S K F and to be recommended for use in this contract will be described in a special report.

DETAILS

1. Shortcomings in the Functioning of Anderometers

No calibration can produce repeatable and reliable bearing vibration readings on a tester which has certain types of shortcomings. If the vibration tester contains electrical or mechanical elements that distort the bearing vibration spectrum beyond acceptable limits or produce poor repeatability, it is necessary to improve these elements before a useful calibration of the equipment can be made.

Existing Anderometers are known to contain some such elements. This report summarizes the results of investigations on the following three elements which have been found always or at least occasionally to cause distortion or poorly repetitive readings:

a. Pickup

b. Mechanical loading device (or method used in applying an axial load to the test bearing).

c. Spindle assembly, including mandrels (this is an occasional source of difficulties).

2. Pickup

Enclosure 1 shows the frequency response curve of a typical Anderometer pickup. (The method used to obtain the curve will be described in a special report.) The curve has a high peak (of about 19 db) between 4000 and 5000 cps, which distorts the reading in the high band (1800-10000 cps) and makes a comparison between bearings in this band very unreliable. This is especially the case when comparing bearings with different vibration spectra in the 1800-10000 cps range.

Because of this disadvantage of the Anderometer pickup, it would be desirable to replace this pickup by one with a flatter response curve. [illegible] has available a type of imported pickups (Type MEA-100) with much flatter frequency response over the complete Anderometer frequency range (50-10000 cps). The response curves of three of these MEA pickups are shown in Enclosure 1, on the same graph as the response curve of the Anderometer pickup. It is seen that the variations from perfect flat response for the MEA-100 pickup are small (within 3 db) with no high resonant peaks below 10000 cps.

The sensitivity of the Anderometer pickup tested is 7 millivolts/inch/sec. in the flat range. The sensitivity of the three MEA-100 Type pickups tested varies from approximately 6 to 9 millivolts/inch/sec. (This variation is acceptable since the gain of the Anderometer amplifier can be adjusted to compensate for the variation between pickups.)

On the basis of measurements on a number of MEA-100 Type pickups the following is recommended:

Recommended, for use with the Anderometer, is a pickup with characteristics specified below:

Flatness of response: Flat within ±0.5db from 50 cps to 7000 cps and within -0.5db to +3db of the same level, from 7500cps to 10000 cps.

Sensitivity: Between 4 and 12 millivolts/inch/sec. in the 50- 7000 cps range.

The MEA-100 pickup has the following further specifications which are satisfactory (but not necessarily required):

Spring load: Approximately 25 grams for a stylus displacement of 0.005 inches.

Weight of moving parts: Approximately 0.08 grams.

Pickups Type MEA-100 satisfying these specifications can be supplied by SKF Industries.

3. Loading Device

The effect of different loading methods has been discussed in previous progress reports. Hand loading was not found to cause excessive distortion of the bearing vibration spectrum, but since readings with handloading repeat poorly with different operators, a mechanical loading device seemed desirable. Existing mechancial loading devices did not, however, give good results. They either distort the spectrum or give poor repeatability. Therefore work was done to develop a new loading device with better characteristics than existing devices. Such a device was recommended in Progress Report No. 3. Enclosure 2 gives the dimensions of the pressure element of this loading device for bearings with bore sizes ranging from 10 to 75 mm. Enclosure 3 shows a sketch of the mechanical arrangement used in applying the load to the pressure element shown in Enclosure 2. Test results indicate that only the pressure element contacting the bearing has a significant influence on the bearing vibration measurements. The detailed design and dimensions of the arrangement of Enclosure 3 have only a minor influence, provided the construction is sturdy enough not to vibrate excessively in testing the bearing. (The system shown in Enclosure 3 utilizes a dead weight as shown) acting at the end of a lever arm to apply the load on the pressure element. A hydraulic or pneumatic system may equally well be used for this purpose. On the above basis, the following is recommended:

Recommended for use with the Anderometer, is a thrust loading element per drawings given in Enclosure 2 of this report.

4. Influence of Spindle Mechanics on Readings

Difficulties experienced in repeating and correlating measurements on several Anderometer type bearing vibration testers operated by SKF, led to an investigation of the effect of the mechanics of the spindle assembly on readings. (In the investigation covered herein, only Medium Band readings were taken.) The investigation covered two Anderometer spindles both of which had been in factory inspection for a number of years, and a vibration spindle of SKF design (here designated as the VKL spindle). One of the Anderometer spindles was tested, also, with six different mandrels to determine the effect of the mandrels.

The test results indicate that the condition of both the spindle and the mandrel influence the vibration readings.

A brief description of the test procedure and results are given below:

The effects of the mechanics of the spindle assembly on bearing readings were determined by measuring, in addition to the vibration of the bearing, the vibration of the spindle with the test bearing mounted. This was done in order to evaluate whether the spindle provides a fixed reference system for measurement of bearing vibrations or whether the vibratory energy of the bearing is divided between outer ring and spindle assembly. In the latter case of course, vibration measured at the outer ring will vary with the properties of the spindle.

The spindle vibration was measured by contacting with the pickup a ball cemented to the center hole of the interchangeable mandrels. Enclosure 4 gives vibration readings - directly comparable to the bearing vibration readings obtained simultaneously - on the ball cemented to the mandrel.

The readings given in Enclosure 4 have been corrected to eliminate the effect of the waviness of the ball cemented to the center hole of the mandrel. For this purpose the waviness of the ball was measured with the ball held in a three-ball seat (the test ball rotating on a seat of three balls, all contacting each other). This arrangement, is used by SKF in ball waviness testing to eliminate the influence of spindle vibrations.

If V_w is the ball waviness reading obtained with the three-ball seat, V_3 the spindle vibration reading (obtained by contacting the ball cemented to the spindle with the pickup), then the spindle vibration with the effect of ball waviness eliminated is:

$$V_s = \sqrt{V_3^2 - V_w^2}$$

This follows from the fact that all the readings are RMS values (expressed in Anderons at 1800 RPM spindle speed) and the assumption that the ball waviness reading is independent from spindle vibration.

To determine the effect of axial load on the bearing (applied by hand) and of radial load from the pickup, the spindle vibration tests were conducted under four different conditions:

(1) No load, no pickup contacting the bearing. The inner and outer race rotate both at spindle speed (no relative rotation between the races).

(2) Only axial load (by hand)

(3) Radial load from Anderometer pickup (approximately 1 lb.), no axial load.

(4) Radial load from Anderometer pickup, axial load by hand.

(Several mandrels were tested for purposes of comparing their effect on results)

It is seen from the readings in Enclosure 4 that for any one mandrel, no significant differences exist between results of tests (2), (3) and (4). Test (1), however gives significantly lower readings than (2), (3) and (4). Since test (1) was the only test on a non-rotating bearing, it may be assumed that the fact that the bearing is rotating (and vibrating) increases the spindle vibration. The type and magnitude of load (for light loads used in the test) do not seem to influence the results.

It is also seen that different mandrels give different spindle vibration readings. A t-test of significance applied to average readings using Mandrels B and D show that these mandrels give significantly different readings (with a probability exceeding 98.5%).

Enclosure 5 gives vibration readings at the O.D. of the hand loaded bearings, measured at the same time as the spindle vibration tabulated in Enclosure 4. These readings are also seen to be influenced by the mandrel used. Differences between mandrels account for a variation of readings attaining 40% between extreme sample averages. This difference is significant with a probability of 97%.

For a tentative theoretical interpretation of the experimental results in Enclosures 4 and 5 the spindle assembly and test bearing are considered a vibratory system with the following characteristics:

Both the bearing and the spindle operate as vibration generators. They also both act as finite mechanical impedances. A part of the vibration, generated by the bearings, is, thus, transmitted to the outer race, another part is absorbed by the spindle. The vibration generated by the spindle is transmitted to the bearing inner ring, hence passes through the bearing, and adds to the bearing outer race vibration.

The vibration V_B generated by the bearings, may be expressed as the sum of the vibration V_o transmitted to the outer race and the vibration V_i transmitted to the spindle.

$$V_B = V_o + V_i \qquad (1)$$

V_s, V_i and V_o are RMS values of vibration velocity. V_o and V_i are linearly additive since the vibrations are coherent and in phase.

The vibration V_s measured on the ball attached to the spindle (with a non-rotating bearing under no load mounted on the spindle) can be assumed to be transmitted to the bearing outer race. The vibration measured by the pickup at the outer race of a hand loaded bearing may therefore be expressed in first approximation as

$$V_1 = \sqrt{V_o^2 + V_s^2} \qquad (2)$$

because the readings are RMS values, and V_o and V_s are assumed to be independent, (they come from an independent source). It is postulated here that the spindle vibrations are not attenuated in the bearing, which is, of course, a simplification.

Following similar reasoning, the spindle vibration measured with the test bearing under load may be expressed as

$$V_2 = \sqrt{V_i^2 + V_s^2} \qquad (3)$$

Combining equations (1), (2) and (3) we get for the total bearing vibration:

$$V_B = \sqrt{V_1^2 - V_s^2} + \sqrt{V_2^2 - V_s^2}$$

V_1 is obtained from Enclosure 5 and V_2 and V_s from Enclosure 4.

The values of V_B computed from the results in Enclosures 4 and 5, are shown in Enclosure 6. If the spindle contribution to measured vibrations were constant as assumed, V_B should then be constant for a given bearing. It is seen, however, that the mean value of V_B varies within approximately $\pm 15\%$ when measured using different mandrels. The difference obtained from mandrels A and C is significant with a probability of 99%, which indicates that the variations in V_B cannot be explained only as random errors. It is believed that vibrations may be absorbed or additional vibrations generated through imperfect fit between mandrels and test bearing and that this fit varies from one mandrel to another. This would explain variations in the computed value of V_B.

Good running accuracy, a tight fit between bearing and spindle and a stiff support between centers can be secured in a test arrangement with the bearing tested on a tapered mandrel between dead centers. It would be reasonable to expect that this arrangement would yield outer ring vibration readings equal to V_B defined above. Tests were conducted in this manner and results are given in Enclosure 7. The bearings generally read higher when tested between the dead centers than the readings obtained on the Anderometer spindle. It is seen, however, by comparing Enclosures 6 and 7, that the average value of V_B computed for the Anderometer spindle over all mandrels (18.3 Anderons) is in agreement with the vibration reading obtained between dead centers (17.2 Anderons).

This shows that:

a) The outer ring vibration reading obtained on an Anderometer or similar device, is not the same as the total bearing vibration. Consequently, a precise definition of the vibratory characteristics of the spindle assembly is necessary to insure repeatable readings and correlation between instruments.

b) The mandrel is a significant variable in determining vibration readings. A precise control of mandrel to spindle fits and other characteristics of the mandrel assembly is needed for repeatable results.

To investigate further whether several Anderometer spindles tested with the same mandrel would produce significantly different results, one hundred 6203 bearings were tested on two Anderometer spindles; designated as Spindle No. 1 and Spindle No. 11. The readings were made on the same amplifier, using the same pickup in both cases. For further comparison, the same bearings were tested on the VKL spindle, using the same Anderometer pickup and amplifier as before.

In conducting these tests, it was found that both Anderometer spindles gave results varying by several Anderons. It was found that the spindles themselves, as well as the flexible couplings connecting spindles and jack-shafts were in poor repair and alignment. Attempts to correct this situation by minor repairs and realignment were unsuccessful. Results obtained at this time were not recorded as they were not repeatable. Both spindles and couplings were then reconditioned with extreme care: journals were relapped, couplings changed and realigned. Readings were then recorded and average readings for the 100 bearings are as follows:

Spindle No. 1	14.67	Anderons (300-1800 cps band)
Spindle No. 11	14.57	"
VKL Spindle	14.55	"

It is seen that the two Anderometer spindles (in good repair) and the VKL spindle read essentially the same in the medium band.

It appears from this test that, with the spindles in good condition, differences between spindles would not influence the results significantly, in the medium band at least. Whether differences between Anderometer mandrels can be similarly reduced by improving the taper between mandrel and spindle has not yet been determined. It is known however, that a mandrel taper of somewhat different design, featuring a drawbar to hold the mandrel in the spindle, will give excellent repeatability (See Enclosure 8 for an illustration of this design).

Recommended that Anderometer spindles be carefully overhauled before calibration. In calibrating, readings on bearings mounted on the spindle tested must be compared to readings on a reference spindle of known characteristics. A recommendation to control the mandrel influence, will be given later.

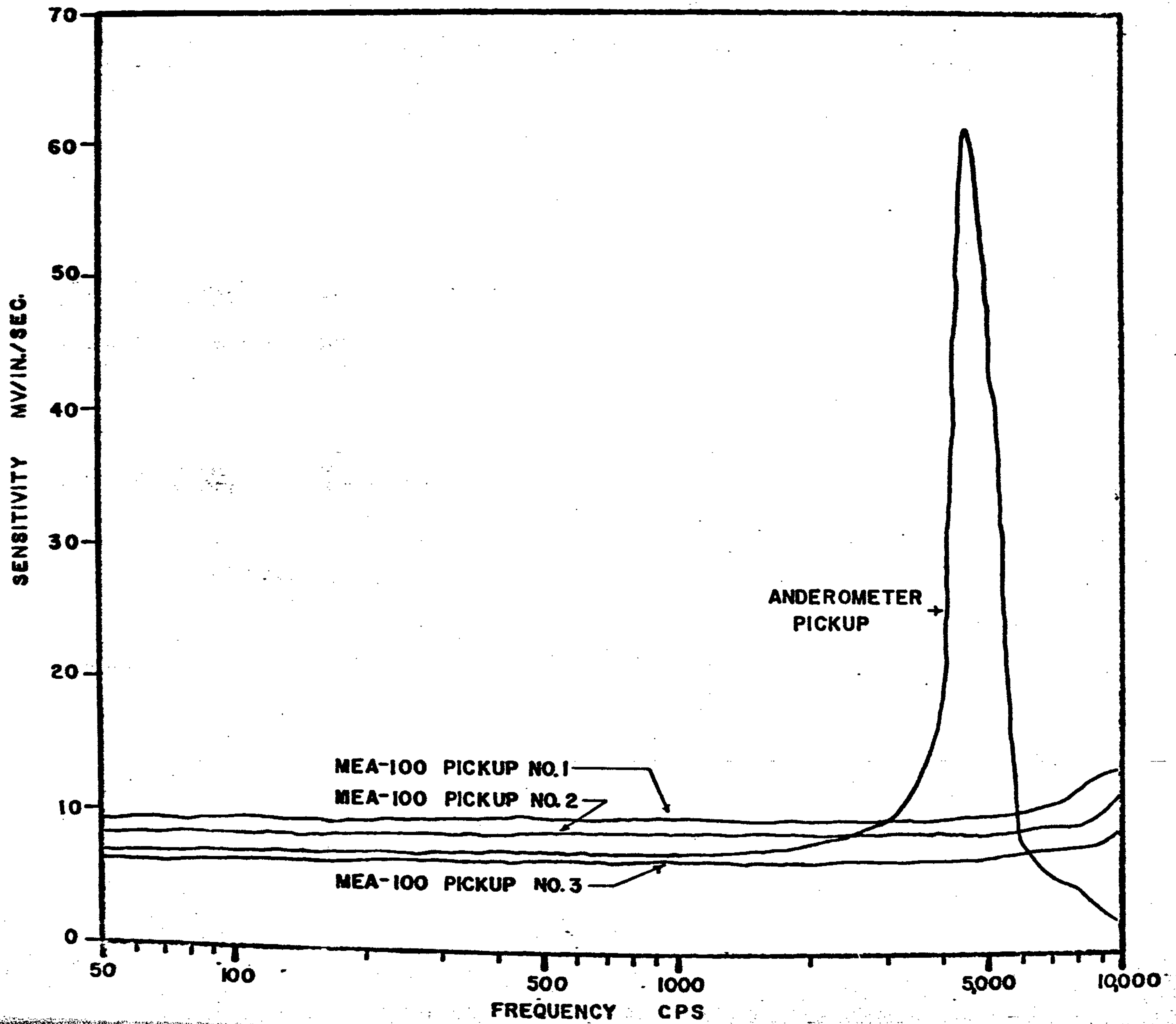
Plans of Work for the Next Reporting Period

A description of the presently used piezo-electric calibration technique will be prepared.

Further experimentation to find a way of minimizing mandrel influence, will be conducted and spindle influence in the high and low bands will be tested.

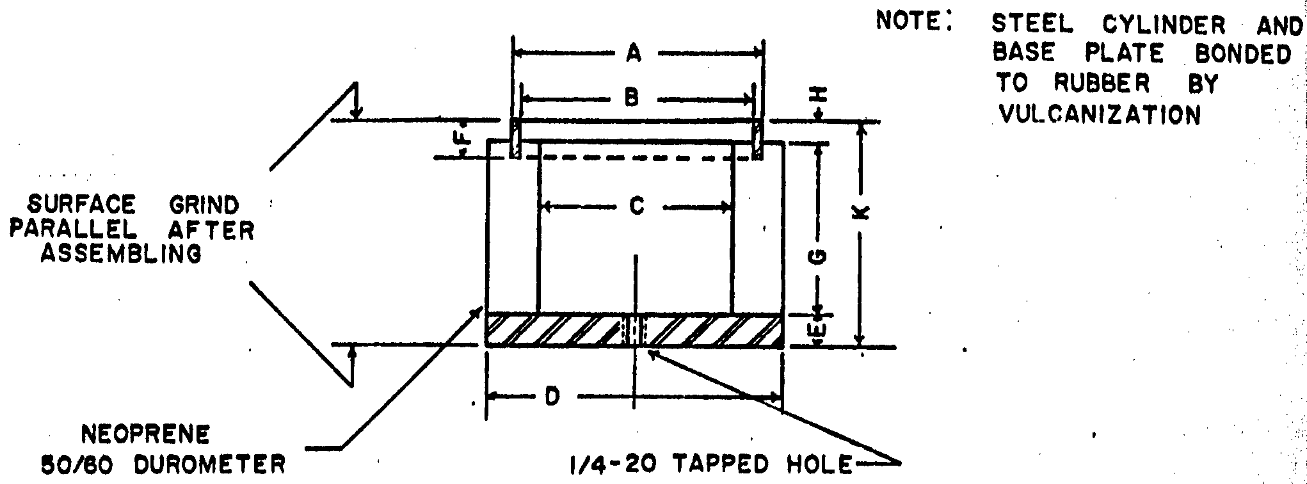
ENCLOSURE 1

RESPONSE CURVES OF PICKUPS

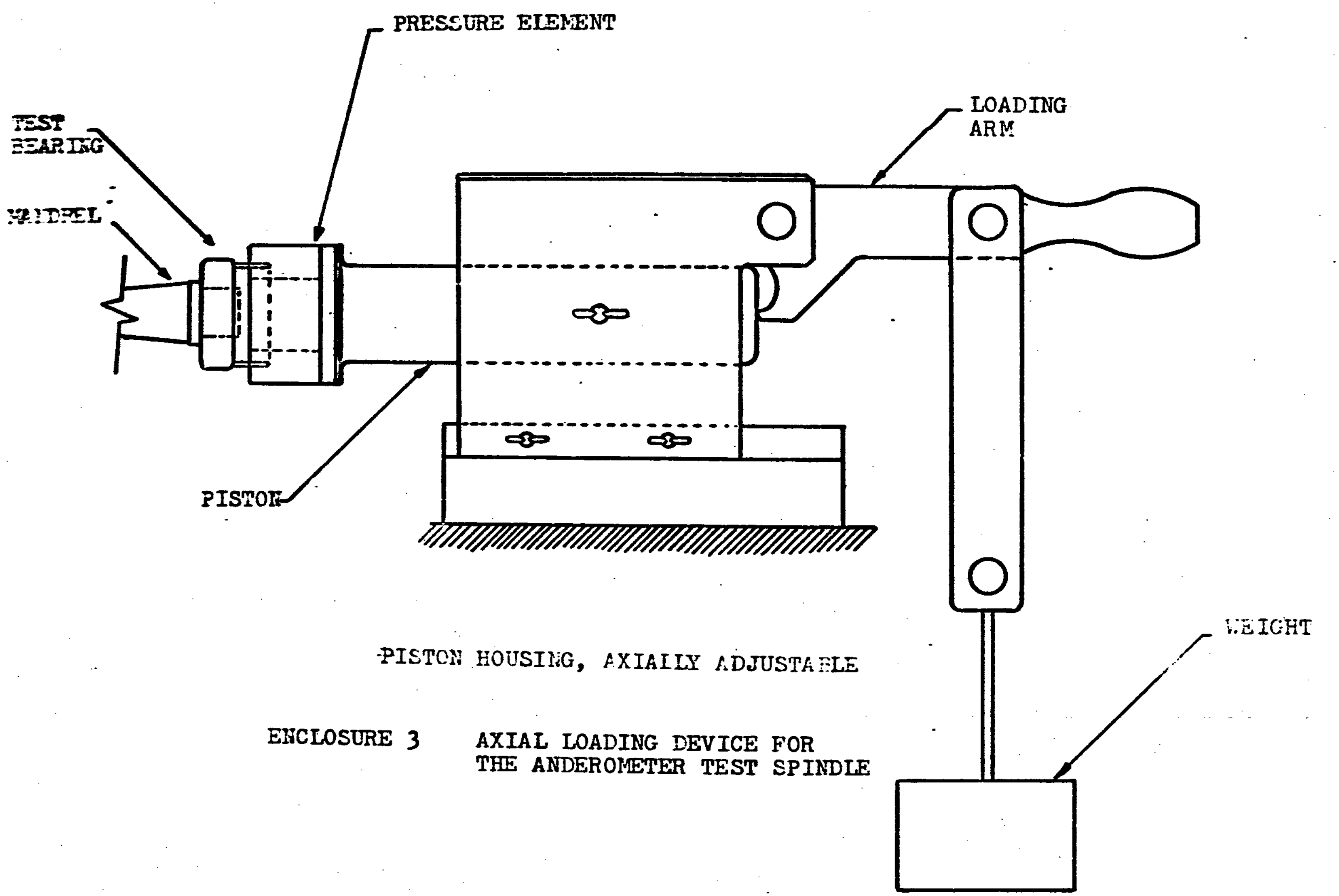


ENCLOSURE 2

PRESSURE ELEMENT FOR LOADING DEVICE



Bearing #		A	B	C	D	E	F	G	H	K
6200		1.11	1.07	27/32	1-11/32	1/4	3/8	3/4	3/16	1-3/16
6201		1.19	1.15	59/64	1-27/64	1/4	3/8	3/4	3/16	1-3/16
6202	6300	1.31	1.27	1-3/64	1-35/64	1/4	3/8	3/4	3/16	1-3/16
	6301	1.34	1.30	1-1/16	1-9/16	1/4	3/8	3/4	3/16	1-3/16
6203		1.50	1.46	1-15/64	1-47/64	1/4	3/8	3/4	3/16	1-3/16
6302		1.54	1.50	1-17/64	1-49/64	1/4	3/8	3/4	3/16	1-3/16
6204	6303	1.73	1.69	1-15/32	1-31/32	1/4	3/8	3/4	3/16	1-3/16
6205	6304	1.93	1.87	1-1/2	2-1/4	5/16	3/8	1	3/16	1-1/2
6206	6305	2.32	2.26	1-59/64	2-21/32	5/16	3/8	1	3/16	1-1/2
6207.	6306	2.72	2.66	2-21/64	3-1/16	5/16	3/8	1	3/16	1-1/2
6208		3.03	2.97	2-41/64	3-3/8	5/16	3/8	1	3/16	1-1/2
	6307	3.09	3.03	2-11/16	3-7/16	5/16	3/8	1	3/16	1-1/2
6209		3.23	3.17	2-53/64	3-9/16	5/16	3/8	1	3/16	1-1/2
	6308	3.37	3.31	2-31/32	3-23/32	5/16	3/8	1	3/16	1-1/2
6210		3.43	3.37	3-1/32	3-49/64	5/16	3/8	1	3/16	1-1/2
6211	6309	3.76	3.68	3-7/32	4-7/32	3/8	3/8	1-1/4	3/16	1-13/16
	6310	4.09	4.01	3-35/64	4-35/64	3/8	3/8	1-1/4	3/16	1-13/16
6212		4.15	4.07	3-39/64	4-39/64	3/8	3/8	1-1/4	3/16	1-13/16
	6311	4.49	4.41	3-61/64	4-61/64	3/8	3/8	1-1/4	3/16	1-13/16
6213		4.55	4.47	4-1/64	5-1/64	3/8	3/8	1-1/4	3/16	1-13/16
6214		4.75	4.67	4-7/32	5-7/32	3/8	3/8	1-1/4	3/16	1-13/16
	6312	4.88	4.80	4-11/32	5-11/32	3/8	3/8	1-1/4	3/16	1-13/16
6215		4.94	4.86	4-13/32	5-13/32	3/8	3/8	1-1/4	3/16	1-13/16



ENCLOSURE 3 AXIAL LOADING DEVICE FOR THE ANDEROMETER TEST SPINDLE

ENCLOSURE 4

VIBRATIONAL VELOCITY OF SPINDLE
(IN ANDERONS, 300-1800 CPS BAND)

READINGS RELATE TO ANDEROMETER PICKUP

Brg. No.	No Axial Load No Pickup Contacting Brg.	No Axial Load Anderometer Pickup Contacting Brg.	Handload No Pickup Contacting Brg.	Handload Anderometer Pickup Contacting Brg.
		Mandrel A		
44	2.2	4.5	3.0	3.8
70	1.7	3.8	4.5	3.8
60	2.2	5.8	4.5	4.5
53	1.7	2.6	3.0	3.4
54	2.2	3.4	3.8	3.4
Average	2.0	4.0	3.8	3.8
		Mandrel B		
44	5.2	5.8	7.2	5.8
70	2.6	7.2	7.2	6.5
60	1.7	5.8	5.8	5.8
53	1.1	3.8	4.1	4.5
54	4.5	3.8	6.5	6.5
Average	3.0	5.3	6.2	5.8
		Mandrel C		
44	2.6	2.2	5.2	4.5
70	1.7	3.4	6.5	6.5
60	1.1	5.8	5.8	5.5
53	0	5.2	3.8	4.5
54	3.0	4.5	5.2	3.8
Average	1.7	4.2	5.3	5.0
		Mandrel D		
44	0	3.0	2.6	2.6
70	0	3.0	2.6	3.0
60	0	3.8	2.6	3.0
53	0	0	1.7	3.8
54	0	2.2	2.2	3.0
Average	0	2.4	2.3	3.1
		Mandrel E		
44	4.5	5.8	5.8	5.8
70	4.1	5.8	4.5	5.5
60	1.7	5.8	5.8	5.2
53	0	3.4	4.1	3.8
54	3.4	3.0	6.5	4.5
Average	2.7	4.8	5.3	5.0
		Mandrel F		
44	1.7	5.8	4.1	5.8
70	0	9.1	5.5	6.5
60	0	5.8	6.5	5.8
53	0	2.6	4.5	4.5
54	0	3.0	4.1	5.2
Average	.3	5.3	4.9	5.6

ENCLOSURE 5

VIBRATION, , OF 6203 BEARINGS

MEASURED ON THE 300-1800 CPS ANDEROMETER BAND

UNDER HAND LOAD

Brg. No.		Readings in Anderons
	Mandrel A	
44		16
70		16
60		11
53		8
54		12
	Average	12.6
	Mandrel B	
44		12
70		15
60		16
53		12
54		17
	Average	14.4
	Mandrel C	
44		16
70		16
60		14
53		20
54		20
	Average	17.2
	Mandrel D	
44		15
70		18
60		16
53		13
54		16
	Average	15.2
	Mandrel E	
44		16
70		16
60		11
53		8
54		12
	Average	14.6
	Mandrel F	
44		12
70		15
60		16
53		12
54		17
	Average	14.0

ENCLOSURE 6

VIBRATIONAL VELOCITY COMPUTED FROM RESULTS IN ENCLOSURES 4 AND 5

Brg. No.		Readings in Anderons
	Mandrel A	
44		18.9
70		19.2
60		14.7
53		10.8
54		14.4
	Average	15.6
	Mandrel B	
44		13.9
70		20.7
60		21.4
53		16.3
54		21.2
	Average	18.6
	Mandrel C	
44		19.4
70		21.5
60		19.2
53		24.5
54		22.1
	Average	21.3
	Mandrel D	
44		17.6
70		21.0
60		19.0
53		16.8
54		17.0
	Average	18.3
	Mandrel E	
44		19.1
70		18.7
60		15.7
53		11.8
54		14.3
	Average	15.9
	Mandrel F	
44		17.4
70		21.5
60		21.8
53		16.5
54		22.2
	Average	19.9
Average of all Mandrels		18.3

ENCLOSURE 7

VIBRATION MEASUREMENTS ON TESTED BEARINGS MEASURED ON MANDREL BETWEEN DEAD CENTERS AT 1800 RPM UNDER HAND LOAD

Brg. No.		Readings in Anderons (300-1800 CPS Band)
44		14
70		18
60		16
53		18
54		20
	Average	17.2

ENCLOSURE 8

VKL VIBRATION TEST SPINDLE