Machining "Mechanical Brains" for Flight Control Systems

North American Aviation's new XB-70A airplane being rolled out from its hangar.

By GILBERT C. CLOSE
Field Editor

Production of "mechanical brains" for complex flight control systems is a challenge that has been successfully met in the precision workshops at Garrett-AiResearch, Los Angeles. These "brains" are so sensitive that if a small housefly happened to alight on a certain part of the operating mechanism, an altitude error reading of more than 40 feet would occur!

The "brain" is the nerve center, so to speak, of the well-known Garrett-AiResearch central air data system. Purpose of this system is to assume control of the airplane at supersonic flight speeds where human reactions fail. In addition to flying the airplane, the "brain" also assumes such diverse responsibilities as navigation, power plant operation, fire control, bombing, missile launching, and other specialized activities. When the "brain" is in control, the human pilot is bypassed as effectively as a spectator at a parade!

The "brain," accorded its rightful technical name, is called a force-balance Mach transducer. It is a very small fulcrum device with a precision bellows providing the "weight" on one end of the fulcrum lever against a constant counterweight on the other end. Incoming signals from the many airplane con-

trol instruments, acting through an E-core transformer, add to or subtract from the bellows pressure, causing the fulcrum lever to become unbalanced. But rather than move up and down like the conventional playground teeter-totter, the instant the fulcrum lever becomes unbalanced, the fulcrum itself moves into a new position to keep the fulcrum lever at an even keel. As this fulcrum moves back and forth, it makes and breaks electrical contacts to route the incoming instrument signals to a computer.

It is the production of this fulcrum device with which the shop is concerned. Many otherwise conservative engineers, who are fully aware of the material and production problems that have been overcome, state flatly that the force-balance Mach transducer is a manufacturing miracle!

For example, all non-sensitive parts of the unit are machined to within 0.0002 of an inch. The jack-screw used to position the fulcrum must turn within 70 millionths of an inch or incur a 7 ft. altitude error. If the tracks on which the fulcrum travels deviate 50 millionths of an inch from flatness, a 5 ft. altitude error occurs. Axial deviation of certain bearings used in the unit must be held within 10 millionths of an inch.

The force-balance Mach trans-

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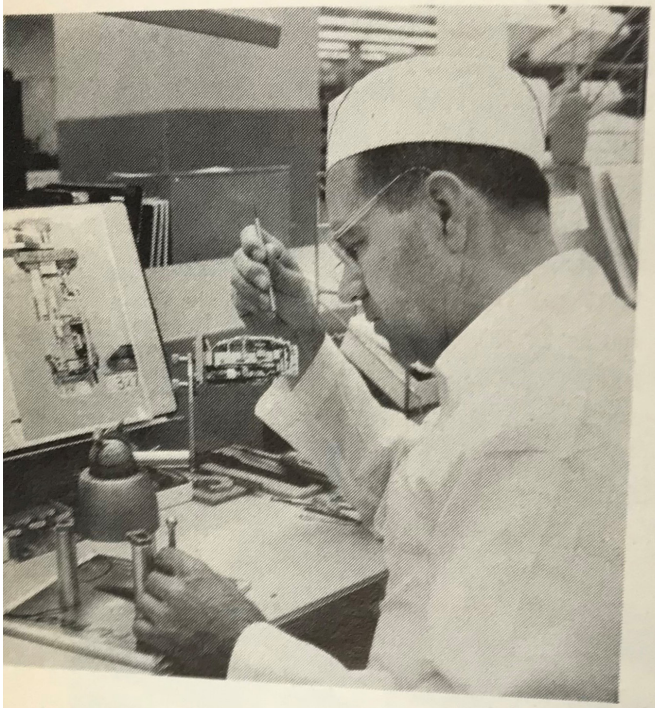


Fig. 2—Technician makes final adjustments on assembled force-balance Mach transducer.

ducer will measure altitude within 10 ft. at sea level, and within 100 ft. at 60,000 ft. It can sense a 3 inch altitude pressure change at sea level, and a 13 inch altitude pressure change at 60,000 ft. It measures air speed 30 times more accurately than an automobile speedometer measures ground speed. It requires 10 days merely to test and check out one of these units, compared to 20 minutes for a precision watch.

Response of the unit to changing environmental conditions is almost instantaneous. If an airplane dives at 80,000 ft. per minute, the force-balance Mach transducer "follows it down," so to speak, indicating accurately at any instant all flight conditions surrounding the rapidly descending airplane. When North American Aviation's experimental RS-70 supersonic Mach 3 airplane was rolled from its hangar for the first time this year, it was equipped with a specialized version of the Garrett-AiResearch central air data system.

Structurally, the force-balance Mach transducer consists of four major components which must be machine shop-produced — (1) the integrated twin flat tracks (Fig. 4) on which the fulcrum carriage travels; (2) the fulcrum carriage itself (Fig. 5); (3) the fulcrum (Fig. 6); and (4) the mount and E-core transformer (Fig. 7).

The blacked-in diagram at the lower right on Fig. 7 shows graphically how the force-balance Mach transducer operates. There is the fulcrum, the fulcrum lever with a fixed weight at one end which is counterbalanced by bellows pressure on the other, and the E-core transformer which, when receiving signals for one of many airplane instruments, is magnetically changed to add to or detract from bellows pressure. When unbalance of the fulcrum lever is threatened, electrical signals cause a precision jackscrew to be driven which moves the fulcrum into a new position to restore balance.

From the engineering standpoint, it should be noticed that the fulcrum is not sharp as in an apothecary scale, but is a round shaft contained between two ball bearings (Fig. 6).

This was necessary as a sharp fulcrum would wear too rapidly under the intense vibratory and dynamic conditions of high speed flight. The tiny metal bellows used to counterbalance the fixed weight on the fulcrum lever was another engineering problem. While a number of so-called precision bellows were available at the time the force-balance Mach transducer was designed, the very best of them would cause a 150 ft. altitude error. Finally a source was located that could produce a bellows so sensitive that error was kept below 15 ft. The weight of a housefly on this bellows will cause an altitude reading error of 40 ft.!

Proper material from which to manufacture the components was another serious problem. This material had to exhibit uniform small thermal expansion and contraction, workability and hardenability, high resistance to corrosion, ability to accept a super finish, heat treatability, and dimensional stability over a period of years.

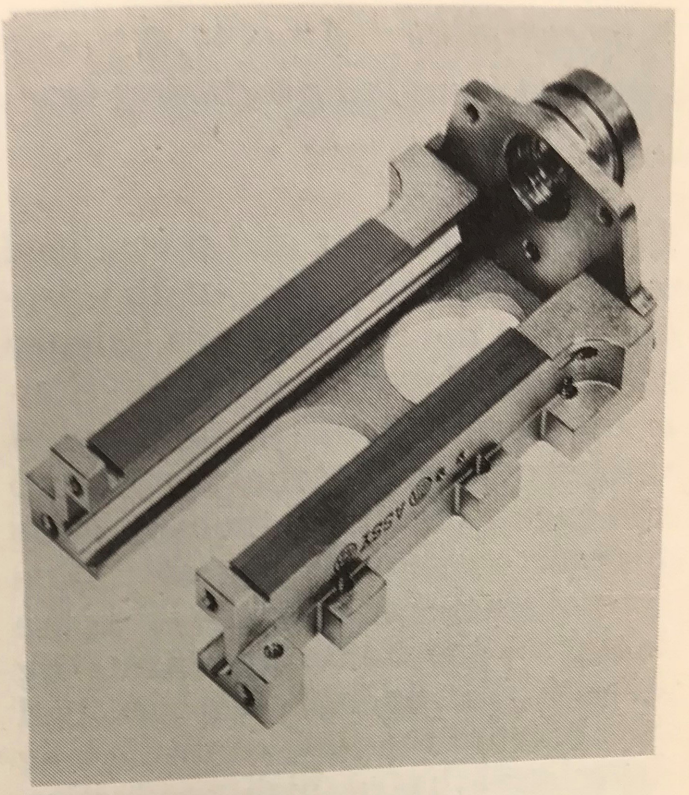
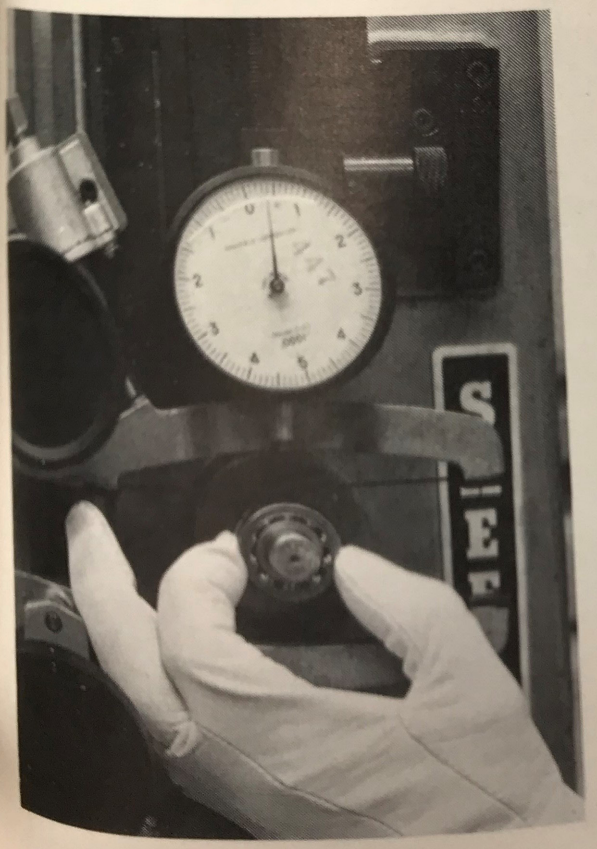


Fig. 4—This illustration shows the tracking component. A 50 millionths of an inch deviation from flat equals 5 feet altitude error.



Final choice was a material in the special stainless steel class exhibiting a very fine grain structure. During the manufacture of each component, this material is subjected to many heat treatments and stress relieving and stabilizing processes. It must be heat treated between each machining or grinding operation to remove work hardness, relieve distortions, and make it ready for the next operation. Even the stresses resulting from touch grinding must be relieved. Yet no heat treatment can be applied after the final grinding or lapping operation as microscopic distortion might be induced. ...uld be noted from the start

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that highly complex and specialized machines are not used in the production of the various force-balance Mach transducer components. Conventional machines are used throughout, with techniques, setup and gaging producing the very close tolerances required. The only tape controlled operation in the lot is the boring of the bearing mounting holes in the fulcrum carriage, and this because the tape controlled jig borer used has a high production potential. As air data computer systems have been installed on thousands of military airplanes, and are being installed on many high performance military airplanes being produced today, all operations must be accomplished quickly, efficiently, and in rapid sequence.

The jackscrew which drives the fulcrum carriage, Fig. 8, is one of the most critical components of the lot. Lead error on this screw must be kept within 70 millionths of an inch. It is pointed out that while this lead tolerance is rather easy to obtain, "drunkenness," or the tendency of the jackscrew to cause the fulcrum carriage to travel on an angle on its tracks, is a far more difficult problem. A special gaging instrument was developed by AiResearch to

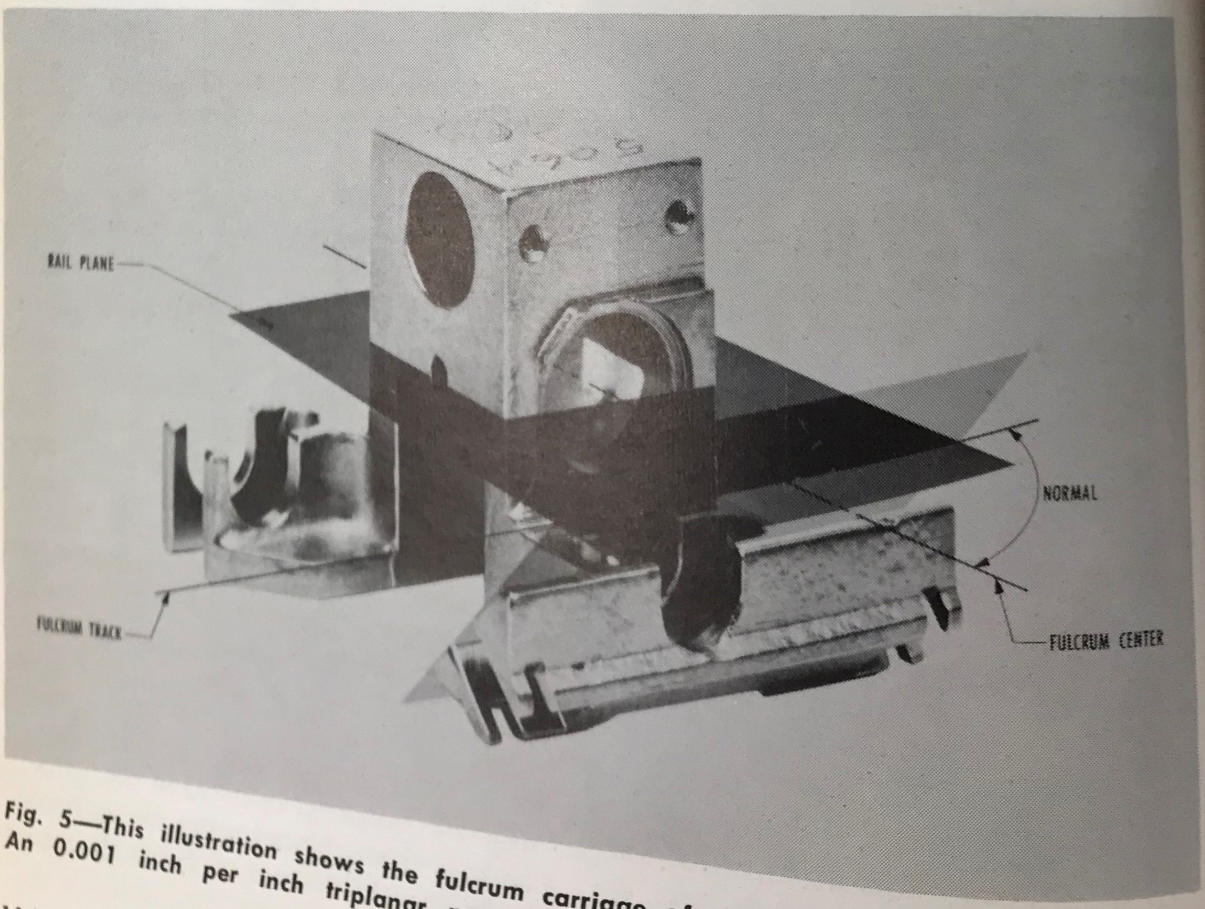


Fig. 5—This illustration shows the fulcrum carriage of the force-balance Mach transducer. An 0.001 inch per inch triplanar normality error equals 25 feet altitude error.

Fig. 6—The fulcrum with its bearings.

detect tolerance deviations which would cause such drunkenness to occur.

As are all other components, the jackscrew is made of a special, fine grain stainless steel. After turning to the proper diameter, a rough thread grind is performed. This is followed by a stress relief heat treatment. Next, the threads are finish-ground, then the lapping sequences start.

Home made split laps of Meehanite cast iron are used with successively finer grades of lapping compound. Toward the later stages of lapping, continual reference to both lineal gages, thread taper gages, and the drunkenness gage are repeatedly made until the exacting results are obtained. A big problem at this point is lap wear, and an intensive research program is now in progress in an attempt to prolong lap life. As it is, the final lapping operations must be accomplished with a relatively new lap which is still well within the microscopic tolerances required.

The integrated tracks for the fulcrum carriage, Fig. 4, when finished are so flat that if pressed together, they become cohesive. The actual track sections are about 2 inches long, and flatness over the entire surface must be held within 11 millionths of an inch. This component is so critical that as much as 0.001 inch oversize in one of the tapped mounting holes is not acceptable. A special alloy is used for the mounting screws.

On this component, the back is first rough machined and broached, then stress relief is given. This is followed by grinding and lapping the back to a flatness which approaches the flatness of the final track surfaces. This care on the back of the unit provides a reference working surface of the required precision. The component is then turned over, mounted on its precision back, and the tracks are planed.

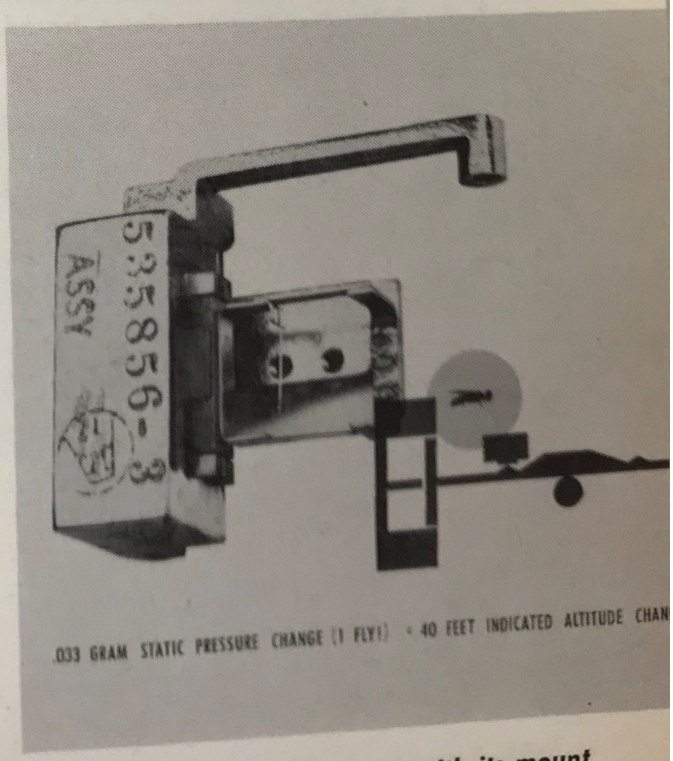


Fig. 7—The E-core transformer with its mount. Note darkened diagram which illustrates graphically how the transducer operates.

"... the bearing mount holes are produced on a tape controlled jig borer."

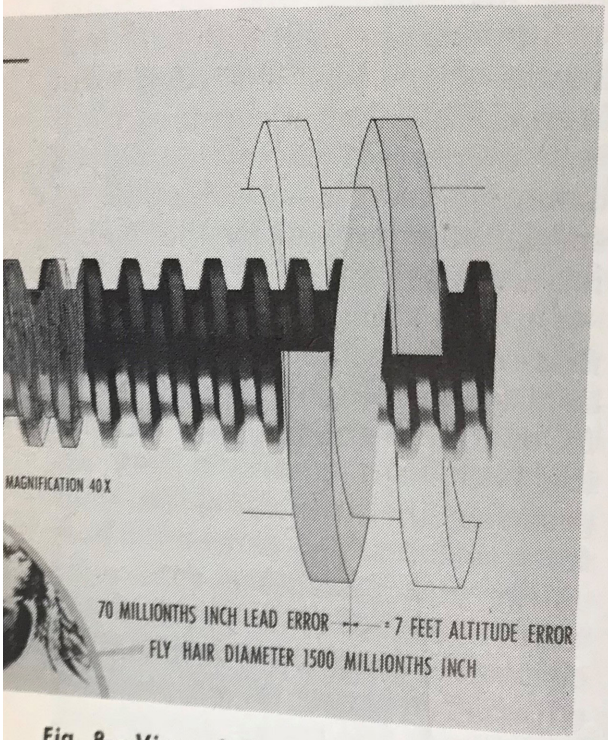


Fig. 8—View of the jackscrew which is used to propel the fulcrum carriage along tracks.

Next, using a double-backed adhesive tape for mounting (to assure absolutely no movement), the tracks are ground, then lapped to requirements. Air gages are used during planing to maintain a constant measurement. Here again progressively finer lapping compounds and frequent gaging are used as the lapped track surfaces near completion. Final inspection requires optical flats.

The fulcrum carriage, Fig. 5, is more a problem of precision distances between points than of precision structural dimensions. Once again drunkenness may be induced unless these distances between points are accurately maintained. The component contains several precision bearings and, as already noted, the bearing mount holes are produced on a tape controlled jig borer.

Line production is used on this item. The base is ground first (after roughing) to provide a working point. All tooling is located from this point until the first bore is made for the fulcrum bearings. Beyond this point, all tool locations are made from these two bores. This is to assure that drunkenness will not occur.

As can be noted in Fig. 5, two precision slots are required at the lower right. Center distances between these slots must be held within 0.0001 inch. This is accomplished by the setup. Two pre-dressed accurately spaced grinding wheels are used to grind the slots simultaneously, with both wheels operating off the same shaft. Thus, there is no possibility of error if the setup is made correctly. Non-critical tolerances on this component are held within 0.0001 inch.

While there is nothing severely critical about the dimensions of the E-core transformer and its associated mount, dimensions are still held within 0.0001 inch on all operating parts. The remainder of the unit, after proper heat treatment (which must be accomplished before any work on the moving parts), is used in its "as cast" form.

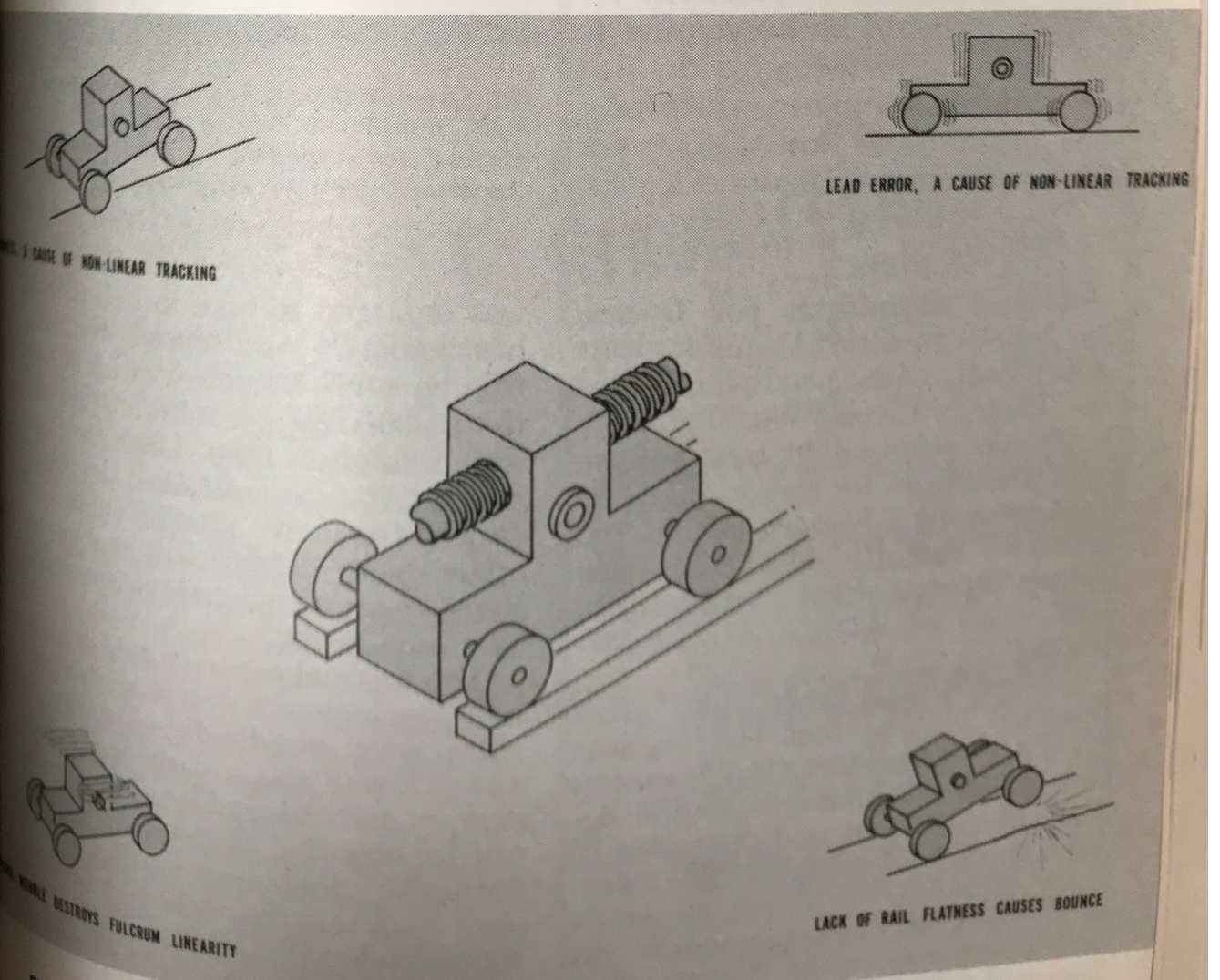
The fulcrum shown between its bearings in Fig. 6 is a routine turning, grinding, and lapping operation to produce a truly circular shaft

within 0.0001 inch in diameter. The bearings are another problem. The best bearings available are purchased, then each and every bearing is given individual inspection.

First, all oil and grease applied to the bearing by its manufacturer are removed by degreasing. Then the bore and axial deviation of the dry bearing is gaged. Axial deviation must fall within 10 millionths of an inch, or sufficient drunkenness will occur to affect the accuracy of the unit.

Acceptable bearings are then carefully weighed in the dry condition, then re-greased with a weighed amount of grease. Thus, each and every bearing, when used in assembly, will meet the required bore tolerances, axial deviation tolerances, and exhibit the same amount of turning friction or torque.

Final assembly of the force-balance Mach transducer is a Class A cleanroom operation where temperature, humidity and air dust count is kept under careful control. Final inspection of all components is also a cleanroom operation, for what appears to be a speck of dust almost invisible to the human eye could



"... except for the tape-controlled jig borer, all work is accomplished on rather conventional shop machines and grinders ..."

turn out to be a microscopic metal burr which could cause malfunction of the unit and might result in tragedy.

Perhaps the most amazing feature concerning the production of these ultra-precision units is that, except for the tape-controlled jig borer mentioned, all work is accomplished on rather conventional shop machines and grinders, with setup techniques and accurate gaging assuring the necessary precision results. This should be heartening to those shop operators who do not have and cannot afford exotic machine installations where costs for same run into the six figure category.

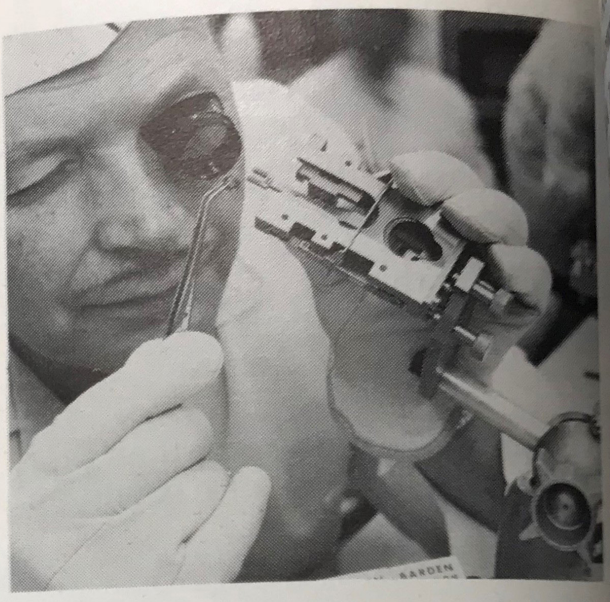


Fig. 10—Installing a bearing in force-balance Mach transducer. Bearing which is first degreased for inspection purposes, has been regreased with a known amount of lubricant.

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Revised Standards For Gears. The American Gear Manufacturers Association with headquarters at One Thomas Circle, Washington 5, D. C., has released 11 new and revised standards for gears, many of them covering advanced design and the most recently developed techniques. Some of them climax almost fifty years of AGMA standards testing.

The Standard Practice for High Speed Helical and Herringbone Gear Units (AGMA 421.05) covers the latest developments in the design, manufacture and operation of high speed units with specific reference to higher hardness materials and sound level measurement and limits. The scope of the standard practice for helical and herringbone gear speed reducers and increasers was enlarged to take in helical and herringbone gear speed reducers that have pitch line velocities of less than 5,000 feet per minute from the former of less than 4,000 feet per minute. It also re-defines "frequent" and "infrequent" starting loads and offers more definitive language on thermal capacity, shaft stresses and overhung loads.

The thermal capacity data of helical, herringbone, and combination spiral bevel speed reducers (AGMA 423.01) was also greatly expanded over an earlier standard. The standard practice for single and double-reduction, double-enveloping worm and helical-worm speed reducers was broadened. It takes in double reduction reducers incorporating helical gearing as the initial reduction. Input power rating data for

surface durability was added to the old surface durability standard which was withdrawn.

Of the 11 new standards three are listed as "tentative," which merely indicates initial printing. The new standards by AGMA number and title are as follows:

(1) AGMA 151.02, "Application Classification for Helical, Herringbone and Spiral Bevel Gear Speed Reducers"

(2) AGMA 203.02, "System—Fine-Pitch On-Center Face Gears for 20-Deg. Involute Spur Pinions"

(3) AGMA 221.02A, "Design Practice—Rating for the Strength of Helical and Herringbone Gears for Enclosed Drives"

(4) AGMA 270.02, "Output Speeds for Gearmotors"

(5) AGMA 271.03, "Ratios for Helical, Herringbone and Combination Spiral Bevel Gear Speed Reducers"

(6) AGMA 420.03, "Practice for Helical and Herringbone Gear Speed Reducers and Increasers"

(7) AGMA 421.05, "Practice for High Speed Helical and Herringbone Gear Units"

(8) AGMA 423.01, "Thermal Capacity of Helical, Herringbone, and Combination - Spiral Bevel Speed Reducers"

(9) AGMA 424.01, "Practice for Helical and Herringbone Gearing for Oilfield Mud Pumps"

(10) AGMA 430.03, "Practice for Speed Reducers and Increasers Employing Spiral Bevel Gearing"

(11) AGMA 441.03, "Practice for Single and Double-Reduction, Double-Enveloping Worm and Helical-Worm Speed Reducers."

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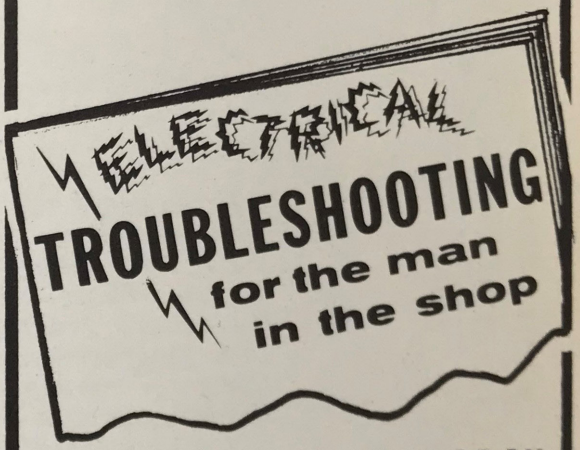

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