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Acceleration Display System for Aircraft Zero-Gravity Research

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ACCELERATION DISPLAY SYSTEM FOR AIRCRAFT ZERO-GRAVITY RESEARCH

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SUMMARY

Acceleration measurement practices for aircraft zero-gravity research have been well established by the experiences of Johnson Space Flight Center's KC-135, Ames Research Center's Learjet, and Lewis Research Center's AJ-2 aircraft. These practices include definition of axes, established values of acceleration ranges and resolutions, and recommendations for acceleration measurement hardware.

In addition to accurate acceleration measurement, the Lewis experience with the AJ-2 aircraft in the mid-1960's revealed the importance of acceleration display methods. During that zero-gravity aircraft program (ref. 1), the position of the zero-gravity displays affected the pilots' ability to accurately fly trajectories.

Lewis adopted the proven practices of acceleration measurement and, with the noted importance of display arrangement, focused attention on the method by which accelerations are displayed to the pilots. The new system was designed to improve the legibility of the displays and to tailor the displays to fit the pilot and Learjet reaction envelope. The principle change was the conversion of the usual needle meter displays to LED bar graph displays positioned and aligned with their respective flight controls. Refinements included fitting the ranges, resolutions, and frequency responses to the pilot and Learjet responses.

Another feature of the Lewis system is the pitch-axis bias switch. The pitch (up-down) axis is the primary axis against which the acceleration environment is judged. A switch allows the selection of one of nine settings for the pitch display's zero reference, allowing the following trajectories to be flown: 0, 1/20, 1/10, 1/6 (Lunar), 1/5, 1/4, 1/3 (Martian), 1/2, and 3/4g.

As a consequence of the iterative determination of specific display characteristics, trajectory accelerations were regularly recorded. These records proved to be invaluable as they provided feedback for immediate post-flight debriefing, evidence of the level of low gravity actually attained, and data for research.

Although specific aspects of the system could be further improved, the present form of the system provides legible, concise, and necessary guidance information that enables the pilots to fly accurate zero-gravity trajectories. Regular use of this system improved the Learjet zero-gravity flight techniques, including one to minimize lateral accelerations. Trajectory data indicate that typical trajectory accelerations can now be sustained within 0.01g for 5 consecutive sec, within 0.02g for 7 consecutive sec, and within 0.04g for up to 20 sec. The system has already been used to successfully fly several zero-gravity

experiments and is now a permanent part of the Lewis Learjet zero-gravity program.

INTRODUCTION

Lewis employs a Gates Learjet for flying zero-gravity research programs. By flying Keplerian trajectories, this aircraft can provide low-gravity environments for up to 22-sec. To accurately fly these trajectories pilots use a new acceleration display system developed at Lewis. Although acceleration display systems already exist for this purpose, Lewis developed its system to improve the human factors aspect of the displays and to incorporate features useful to Lewis research programs.

The principle behind Keplerian trajectories is that zero gravity exists within objects undergoing free fall. A Keplerian trajectory is a free fall path, and thus zero-gravity environments can be produced inside aircraft traversing Keplerian trajectories. In practice, the critical portion of the trajectory is flown by actively nulling the aircraft's accelerations. Various methods of monitoring aircraft accelerations include feel, watching the motion of loose objects within the aircraft, and the use of acceleration displays. Although seat-of-the-pants flying or watching floating objects allow for occasional transitions into zero gravity, accelerometer-driven displays are necessary to smoothly maintain the aircraft in the research regime of hundredths of g's.

Acceleration display systems that are sensitive at the hundredth of a g level are not, in general, in enough demand to be commercially available, thus researchers have had to build their own systems. The Ames Research Center's Learjet and Johnson Space Flight Center's KC-135 zero-gravity display systems were excellent starting points for the Lewis system. Lewis, aiming to improve how accelerations are displayed to the pilots, chose a different display format and then evolved the displays to fit the Learjet and pilot responses. A bias feature, which allows fractional g trajectories to be flown, and the practice of regularly obtaining permanent records of flight performance also became features of the new Lewis system.

This report describes the features, design, calibration, and testing of the Lewis system. Specific circuit schematics and system specifications are included as well as representative data traces from flown trajectories. Other observations learned from developing and using this system are mentioned where appropriate.

ESTABLISHED PRACTICES AND NEW DIRECTIONS

Since the goal of flying zero-gravity Keplerian trajectories is to null accelerations, the most direct guidance instrument is an acceleration display. Accurate trajectories are difficult to fly as they span large variations of acceleration and airspeed (fig. 1). The variation in acceleration (1 to 3 to 0 to 2 to 1g) is not only fatiguing to the aircraft and crew, but the 0g portion of the trajectory induces problems with aircraft's fluid systems (fuel, hydraulics, and engine oil). The large variation in airspeed (360 to 150 kn)

induces difficulties with the 0g portion of the trajectory since flight controls vary with airspeed. Those problems, other day to day variations, and weather make some sort of acceleration display mandatory for flying accurate zero-gravity trajectories.

Aircraft zero-gravity display systems define acceleration axes according to figure 2 and measure acceleration with servotype accelerometers mounted near the aircraft's center of gravity. Other usual characteristics of previous zero gravity display systems include (1) displaying the pitch (up-down) and thrust (back-forth) axes using needle-meter displays, (2) extending the pitch axis range to 3g in order to include entry maneuver accelerations, (3) having display resolutions on the order of hundredths of g's with data accuracy on the order of thousandths of g's, and (4) providing the ability for data recording. Naturally, attention is also placed on accurately aligning and calibrating the system.

Lewis incorporated the following additional features: (1) the lateral (side-side) axis is measured and displayed along with the traditional pitch and thrust axes; (2) the displays are located and aligned with their respective flight controls; (3) LED dual polarity bar graphs are used as the display format; (4) the ranges, resolutions, and frequency responses of the displays were evolved to fit characteristics of the pilots and of the Learjet; (5) the pitch axis uses a logarithmic scale about zero; and (6) a pitch axis bias switch allows trajectories to be flown around select fractional g levels. Obtaining permanent trajectory performance records also became a regular practice with the Lewis zero-gravity program.

NEW ACCELERATION DISPLAYS

Three LED bar-graph displays are used to present the three acceleration axes. Each display is aligned as nearly as possible with the axis it represents to simplify pilot interpretation and reaction. A bar-graph display operates like an object drift indicator with the position of the lit LED representing the direction and extent a floating object would accelerate inside the aircraft. This is a very natural visual affect, and lacks the disadvantages inherent with real object drift where objects need room to drift and where steady-state motion is easily misinterpreted as acceleration.

Since different zero-gravity flight functions are separately controlled by the pilot and co-pilot, their respective acceleration displays are separately located as shown in figure 3. The pitch and lateral displays, which are a function of the yoke and rudder controls, are located in front of the pilot who controls the yoke and rudder. The thrust display, which is a direct function of throttle control, is located in front of the co-pilot who controls the throttles. Ideally, the thrust axis should be aligned fore and aft, but there is no practical location allowing this alignment. The alignment and polarity were arrived at by pilot preference and by the availability of panel space.

Although visually similar to needle meters in operation, dual polarity LED bar graph displays take up less panel space, have no moving parts, do not have parallax problems, and can be more easily aligned with the axes they represent. The disadvantages are that the LED's are not legible in direct

sunlight and have limited data resolution due to the discrete nature of a bar graph's individual LED's.

ITERATIVE DETERMINATION OF RANGES, RESOLUTIONS, AND FREQUENCY RESPONSE

The Lewis system's ranges and resolutions were iteratively evolved with flight testing to determine the most appropriate settings for the Learjet and pilot responses. Range is a display's full scale and must be large enough to encompass the maximum g levels to be experienced in the trajectory. Resolution is the smallest increment to which the display can be read, and must be within the accuracy to which the trajectory can be flown. The initial pitch and thrust ranges and resolutions were copied from the systems of Johnson and Ames, and the initial range and resolution for the lateral axis was deduced from an Ames experiment's data. As the system evolved, the pitch and thrust ranges decreased, and their resolutions became finer. The final system characteristics are shown in table I.

The pitch axis display is not only used to measure the fine region about $0g$, but is also used to monitor the trajectory's high g entries and exits. To pick the best format for displaying both the $0g$'s high resolution and the full $3g$ range, the following methods were tried in flight: (1) a manual switch to change the entire display's sensitivity by a factor of 10; (2) a split scale where the inner ± 10 LED's are more sensitive than the outer ± 10 LED's; (3) a split scale and a manual gain switch; and (4) a split scale where the inner scale is a logarithmic progression having a finer resolution than the outer LED's. Figure 4 graphically shows this final configuration, indicating the g levels with respect to LED readings. Another method considered was the use of a separate, standard aircraft g meter for monitoring the high g maneuvers and using all of the ± 20 LED's for the sensitive region. This method was not tried because of limited cockpit panel space and because a smooth visual transition from the high g instrument to the fine g instrument could not result from using separate displays.

A low-pass filter built into the signal conditioning circuits takes out acceleration changes that are faster than the reaction times of the aircraft and pilot and also removes the higher frequency signals that are beyond the display's response time. The final value of the filter's cutoff frequency, $1\frac{1}{2}$ Hz, was arrived at by a combination of pilot preference and of a decision to restrict the circuit design to standard values.

SYSTEM DESCRIPTION

The system is physically composed of (1) the accelerometer block, (2) the power supply and interface box, (3) the signal conditioning and thrust axis display, and (4) the pitch and lateral axes display. The accelerometer block includes three-servoaccelerometers orthogonally mounted on an adjustable tri-axial base which allows fine tuning of the alignment of the accelerometers with respect to the aircraft. It and the power supply and interface box, the connection point for the system's components, are located near the aircraft's center of gravity in the luggage area of the Learjet (see fig. 5). The signal conditioning and thrust axis display contains all the signal conditioning circuits. It and the pitch and lateral axes display are located in the cockpit. (See fig. 3)

The system functions as outlined in figure 6, the system functional block diagram. (Schematics are included in the appendix.) Starting at the top of the block diagram, the analog outputs of the accelerometers are passed through low-pass filters (three-pole with a cut-off frequency of $1\frac{1}{2}$ Hz) and then through amplifiers incorporating trim adjustments for gain and bias. The signals are then routed to auxiliary data buffers and to their respective displays. The accelerometer characteristics are listed in table II. A bias can be added to the pitch axis display signal (not to the auxiliary data signal) by selecting one of the nine settings, including zero, of a voltage divider stack. This is the pitch axis bias feature.

The thrust and lateral displays are functionally alike. The signal from the signal conditioning circuit goes through a scale-defining amplifier and then to a linear stack of comparators for the positive-indicating LED's and through an inverter to a linear stack of comparators for the negative-indicating LED's. Both the inverted and noninverted signals are input, through blocking diodes, to a zero comparator for the zero-indicating LED pair. Two LED's are used to indicate zero rather than a single LED to provide symmetry about the center reference LED.

The pitch axis bar graph has two regions. The inner ± 10 LED's have a high resolution logarithmic scale, and the outer ± 10 LED's have a low-resolution linear scale as previously described in figure 4. The circuitry does not include a scale defining amplifier nor the same zero comparator configuration as used with the other axes. The zero comparator is driven through an amplifier possessing a slight bias to offset the zero comparator's asymmetric behavior. The dual sensitivity of the bar graph is accomplished by using different voltage divider proportions for the inner and outer comparator stacks. The inner stacks are set to correspond to a 0.06g range and the outer stacks to a 3g range. The inner ± 10 LED's are driven from comparators with logarithmic increments to provide finer resolution about zero than would otherwise be possible with a linear scale maintaining the 0.06g range.

CALIBRATION

The system accuracy has two aspects: bias error and gain error. The bias error, the difference in signal zero to true zero, is the most important error of the system. The gain error, the error in signal amplification, is small and rather unimportant since the critical data are of relatively low amplitude. The values listed in table III are results of the final system calibration. Although referenced to a specific date, no day to day variations in excess of the listed precisions were ever noticed with this system's calibration characteristics.

The system is calibrated in two operations: The bench calibration accurately matches the displays with reference g loadings, and the aircraft calibration accurately aligns the calibrated system within the aircraft.

The bench calibration used the dividing head (fig. 7) to induce varying amounts of the Earth's reliable $1g$ onto each accelerometer. The dividing head's platform can tilt an accelerometer to any angle from 0 to 360° that correspondingly induces any g loading within $\pm 1g$. A bubble level, accurate to 0.0005 in./ft, is used to level the dividing head's platform which, when

combined with the head's positioning accuracy of ± 1 arc sec, provides a calibration reference of $\pm 1g$ accurate to $\pm 0.000045g$.

With an accelerometer mounted to the head's platform, the associated display's signal conditioner bias and gain are adjusted to achieve correct display indications with respect to the g 's induced by the dividing head's orientation. The bias is set to obtain symmetric-about-zero triggering thresholds for the display's individual LED's, and gain is set to obtain correct full-scale readings for corresponding full-scale g loadings. The LED's triggering thresholds are referenced for the calibration as they are necessarily precise, reliable, display points.

The display bias values for each axis shown in table III are the average differences of one polarity verses the other polarity's LED triggering per g loading for about 20 data points. The precisions listed are the standard deviations of the data points. The auxiliary data bias values for each axis listed in table III represent the worst case of about 50 auxiliary output per reference g loading data points, after a bias correction. The auxiliary data bias correction is the output voltage at a $0g$ reference input, which is compensated for at the recording device. The auxiliary data correction is necessary due to the lack of individual auxiliary output bias trims. The gain error for each axis is the average difference in corrected auxiliary output per reference g loadings for about 5 data points. All the values shown in table III include the possible error of the dividing head.

With the bench calibration complete, the next operation is to properly align the accelerometers within the aircraft. This alignment is done by leveling the aircraft, and adjusting the accelerometers' base to level, as verified by the data from the thrust and lateral axes as well as by standard bubble levels on the triaxial block (a $\pm 0.1^\circ$ electronic level was also used). Next, the triaxial block is rotationally aligned with the longitudinal and lateral aircraft axes which can only be done by physical measurements. Fortunately, this adjustment does not need to be any better than about $\pm 0.5^\circ$, which corresponds to less than a $0.0004g$ error, in a $0.05g$ cross axis loading.

The misalignment errors for the accelerometers' mounting block (table III) include both the triaxial block's machining accuracy (0.002 in./ft) and the manufacturer's specifications for each accelerometer. The misalignment errors of the triaxial mounting block in the Learjet refer to the possible error in aligning the system in the aircraft. Figure 8 shows how misalignment affects the system. Cross axis loadings during the $0g$ portion of the trajectory are less than $0.05g$'s. In the figure, the erroneous acceleration loading on the misaligned axis is given by

$$E = A \sin \theta$$

The term $\sin \theta$, representing the degree of misalignment, has the conventional units of mg/g . For example, a mislignment of $8.7mg/g$ and a cross axis loading of $0.05g$ gives

$$E = 0.05g \times 8.7mg/g = 0.4mg = 0.0004g$$

TEST EXPERIENCE

During the iterative development and check-out of the display system, no less than 150 zero-gravity trajectories were flown. Most of those were in support of experiments (flammability limit experiments, liquid transfer experiments, and monkey space-flight indoctrination.) The regularly recorded flight data (trajectory accelerations) were used to improve pilot proficiency, provide hard copy evidence of actual aircraft attainable zero-gravity environments, and to check research data. Typical examples of flight data are presented in figures 9 to 11. Figure 9 shows that typical pitch axis accelerations can be held within 0.01g for 5 consecutive sec, within 0.02g for 7 consecutive sec, and within 0.04g for up to 20 sec. The thrust axis accelerations can be held within 0.01g for the duration of the trajectory, and the lateral axis accelerations can be held to within 0.02g for the duration of the trajectory. An example of a better than average trajectory is presented in figure 10, where the pitch axis was held to 0.01g for 12 consecutive sec., within 0.02g for 16 consecutive sec, and within 0.04g for up to 18.5 sec. An example of a fractional g trajectory is presented in figure 11.

An example of the usefulness of taking regular flight data, and of the importance of the lateral axis display, was the improvement in flight techniques to correct lateral drift. During the early flight trials, when the lateral display was not operational, it was obvious to the pilots from drifting objects that lateral accelerations were present.

The regular data allowed immediate postflight debriefing, where the pilots could assess the results of whatever corrective methods tried during the flight. The working lateral display provided the necessary feedback for real time assessment of flight changes and, eventually, for proper adjustment of rudder trim to minimize lateral accelerations. Now, before entering a trajectory, in 250-kn straight and level flight (a convenient airspeed within the 300- to 150-kn range experienced throughout the zero-gravity portion), the rudder is trimmed so that the lateral display indicates zero acceleration. During the trajectory, no further attempts are made to correct the minor fluctuations in lateral acceleration, as that complicates the flight controls of the more critical axes. Lateral accelerations can now be held within 0.02g for the full duration of the 0g portion of the trajectory (figs. 9 to 11).

POTENTIAL IMPROVEMENTS

Three possible improvements of the system are the addition of auxiliary data bias trims, the smoothing of the transition from the pitch-axis high range to the zero-gravity range, and the correction of the pitch-axis zero comparator.

A useful improvement for data recording would be the addition of bias trim components to the auxiliary data buffers to compensate for any difference in the bias of the display and that of the auxiliary data signal. Fortunately, recording devices have bias adjustments; thus this difference can presently be trimmed out at the recording device.

To obtain smoother transitions from the outer region of the pitch axis to its fine-resolution inner region, the outer and inner stacks should be tied to

independent voltage references which would then allow the use of a logarithmic scale for both the inner and outer regions. As the system is currently configured, the high end of the inner stack is tied directly to the low end of the outer stack, which results in a discontinuity in display resolution at the junction shown in figure 4. (This configuration poses no problems with the thrust axis, as the sensitivities of its inner and outer regions are equal.) To reduce the discontinuity, the low ends of the inner and outer stacks should be tied directly to ground and their high ends should be tied to separate voltage references. This separation would allow the use of logarithmic stacks for the full display.

Another area for improvement is the pitch-axis zero comparator. The thrust and lateral axes' zero comparators work fine, but the asymmetrical behavior of the pitch axis lead to its removal. This feature could be restored by first removing the bias on the prezero comparator amplifier, adding an inverter and inputting both the inverted and noninverted signals through blocking diodes to the zero comparator, as is done with the thrust and lateral axes. The gain of the amplifier into this configuration would need to be trimmed to properly set the on-off thresholds of the zero LED's with respect to the first nonzero LED's.

CONCLUSIONS

The acceleration display system described in this report is now a permanent part of the Lewis Learjet as configured for zero-gravity research. The system followed the past practices of acceleration measurement, yet improved the methods of acceleration display. Attention was focused on ensuring that the displays were easy to follow and that they only covered ranges and resolutions appropriate for the Learjet and pilot responses. As a result, the pilots have improved their zero-gravity flight performance, including the minimization of lateral accelerations. Accurate zero-gravity trajectories, as well as select fractional gravity trajectories, can now be routinely flown and documented.

REFERENCES

1. Useller, J.W.; Enders, J.H.; and Haise, F.W., Jr.: Use of Aircraft for Zero-Gravity Environment. NASA TN D-3380, 1966.

TABLE I. - DISPLAY RANGES AND RESOLUTIONS

	Thrust axis, X	Lateral axis, Y	Pitch axis, Z
Beginning range	±0.2g	±0.1g	^a ±0.3g
Final range	±.1g	±.1g	a,b±.06g
Beginning resolution	0.01g	0.01g	^a 0.01g
Final resolution	.005g	.01g	a,b0.002g to 0.013g ^c .3g

^aFine.
^bLagarithmic.
^cCoarse.

TABLE II. - ACCELEROMETER CHARACTERISTICS^a

Performance:	
Current sensitivity	1.33 mA/g ±10 percent
Voltage sensitivity range	100 to 0.25V/g
Frequency response:	
0 to 10 Hz	±0.1 percent
10 to 300 Hz	±5 percent
Power supply voltage	±13 to ±18 V dc
Quiescent current per supply	20 mA
Maximum resolution and threshold	<0.000001g
Linearity	<20µg/g ² to 30g
Hysteresis and repeatability	0.001 percent full scale
Bias/zero unbalance maximum:	
Range	±10 mg
Typical	3 mg
Bias temperature coefficient	30µg/°C
Scale factor temperature coefficient (maximum)	180 ppm/°C max.
Axis alignment/transverse sensitivity	0.0005 to 0.002g/g
Environmental:	
Operating temperature range	-55 to 107 °C
Static overload	100g
Shock	250g peak, 6 msec
Vibration, sine 20 to 1800 Hz	40g peak
Physical:	
Weight	80 grams
Seal	Welded hermetic
Size	24.3 by 25.5 mm

^aManufacturer's specifications

TABLE III. - SYSTEM ACCURACY AS OF FEBRUARY 1986

	Thrust axis, X	Lateral axis, Y	Pitch axis, Z
Display bias Bias direction	0.0007g±0.0009g Rearward	0.0001g±0.0003g Left	0.0013g±0.0005g Upward
Auxiliary data bias (after correction)	±0.0034g	±0.0036g	±0.0021g
Auxiliary data correction	0.015V	0.014V	0.019V
Gain error (percent signal)	±0.3 percent	±0.1 percent	±0.2 percent
Misalignment:			
Accels on block	0.31mg/g	0.33mg/g	0.46mg/g
Block in lear	8.7mg/g	8.7mg/g	8.7mg/g

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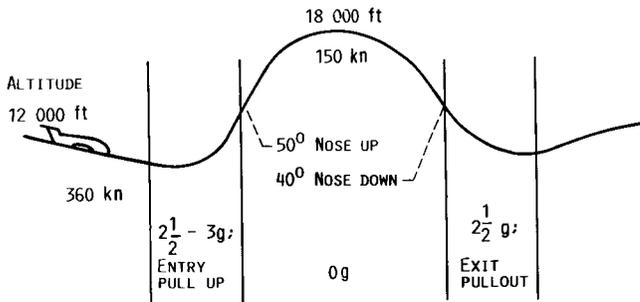


FIGURE 1.- TYPICAL LEARJET KEPLERIAN TRAJECTORY.

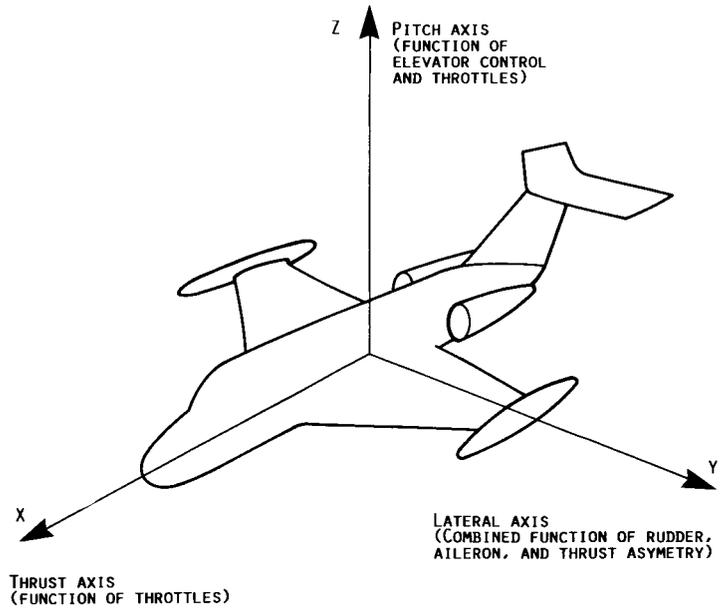


FIGURE 2.- AIRCRAFT AXES.

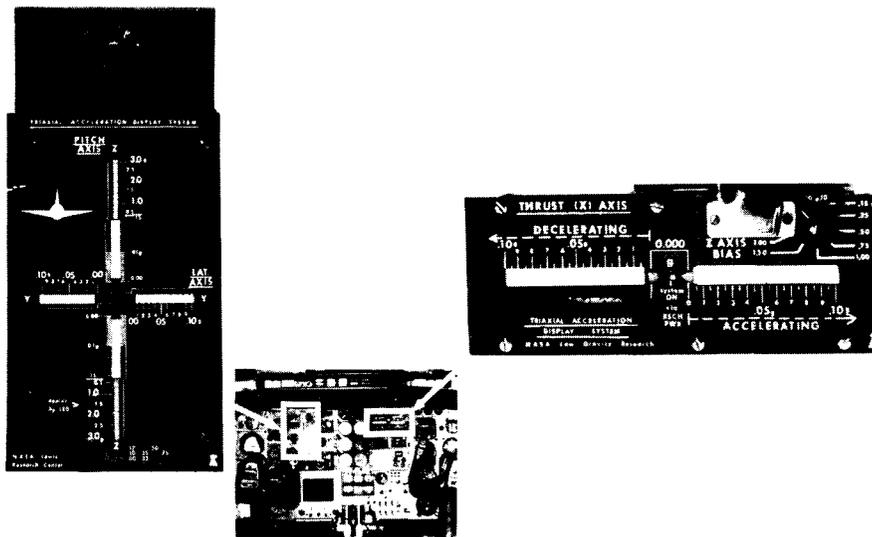


FIGURE 3. - LED LINE GRAPH ACCELERATION DISPLAYS. (BIAS SELECTIONS SHOWN HERE ARE VALUES THAT WERE TRIED BEFORE THE FINAL SYSTEM VALUES DESCRIBED IN THE TEXT.)

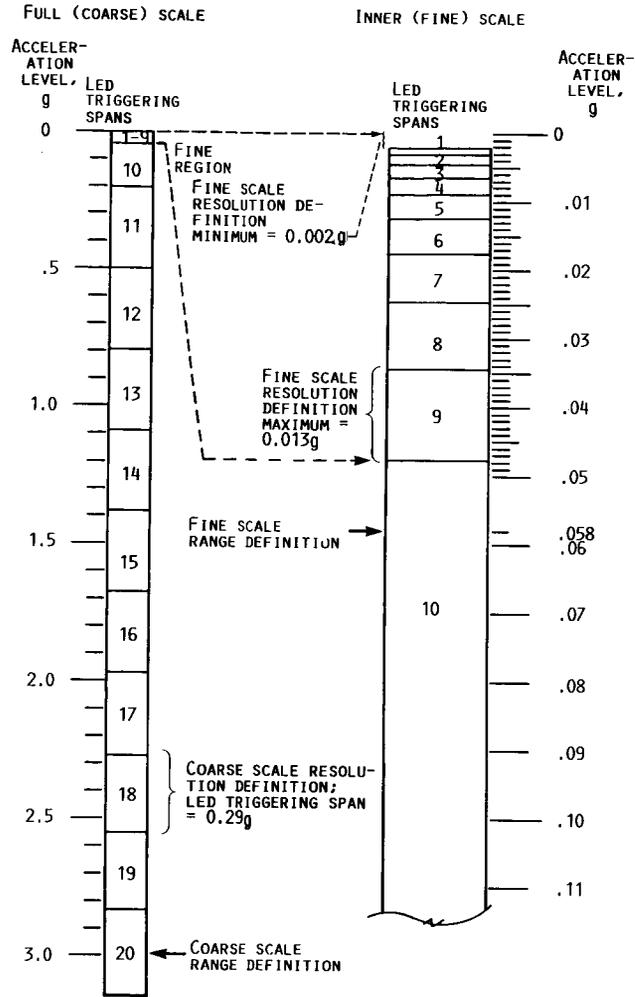


FIGURE 4. - FINAL PITCH AXIS SENSITIVITY. ONLY ONE POLARITY (HALF) OF DISPLAY SHOWN.

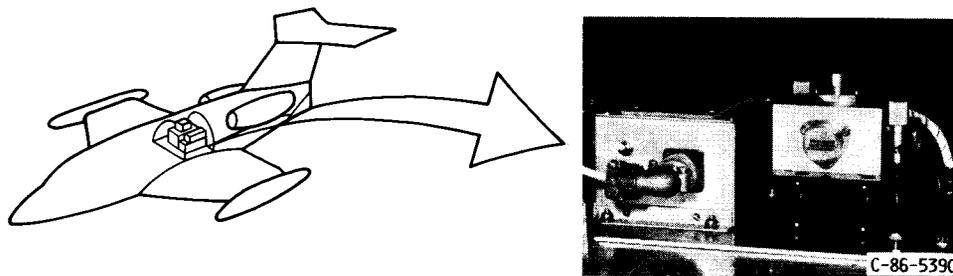


FIGURE 5. - ACCELEROMETER LOCATION ABOARD LEARJET. THE POWER SUPPLY AND INTERFACE BOX IS ON THE LEFT OF THE PHOTOGRAPH AND THE ACCELEROMETER BLOCK IS ON THE RIGHT.

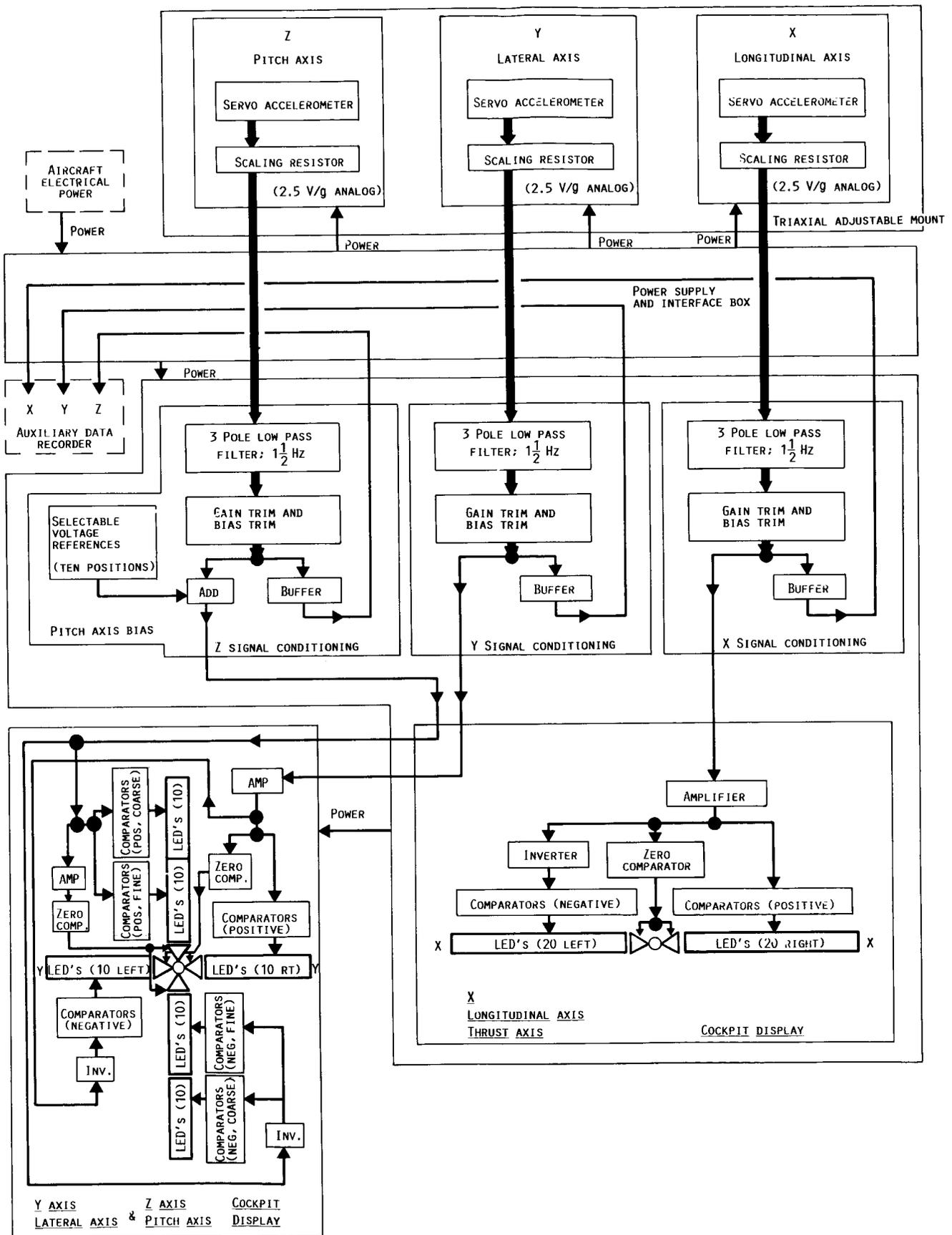


FIGURE 6.- SYSTEM FUNCTIONAL BLOCK DIAGRAM.

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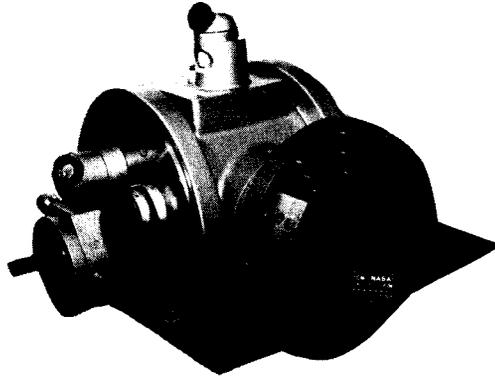


FIGURE 7. - DIVIDING HEAD USED FOR
BENCH CALIBRATION.

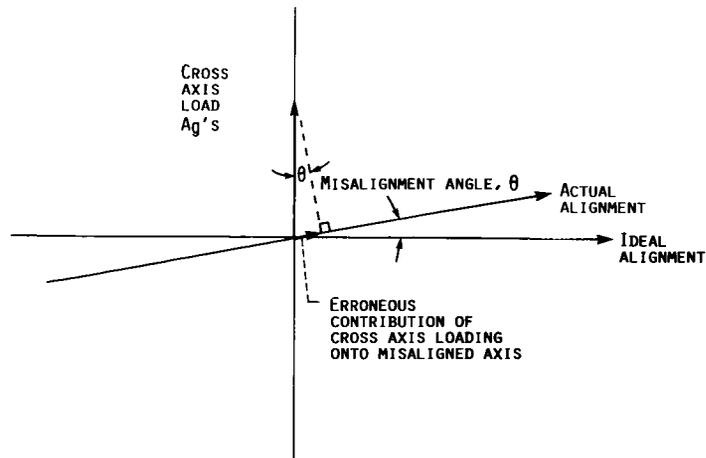


FIGURE 8.- EFFECT OF MISALIGNMENT ON ACCURACY.

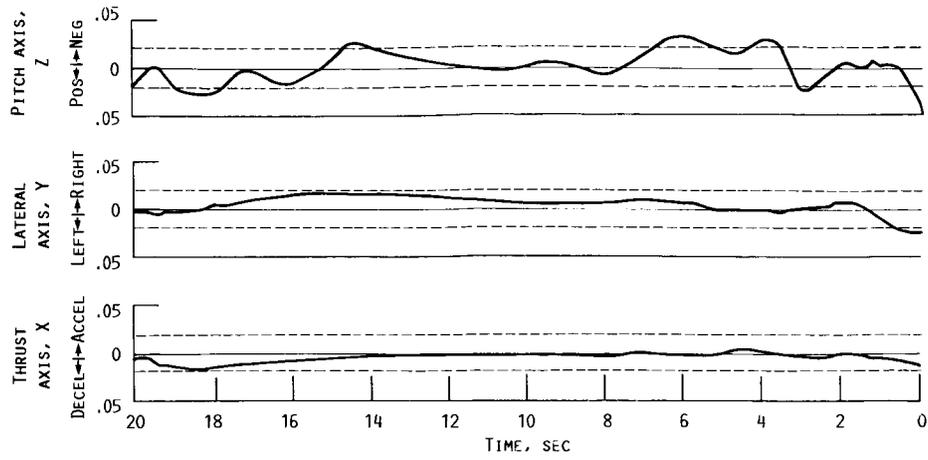


FIGURE 9.- TYPICAL TRAJECTORY. TRAJECTORY 3; FLIGHT DATE, JULY 3, 1985.

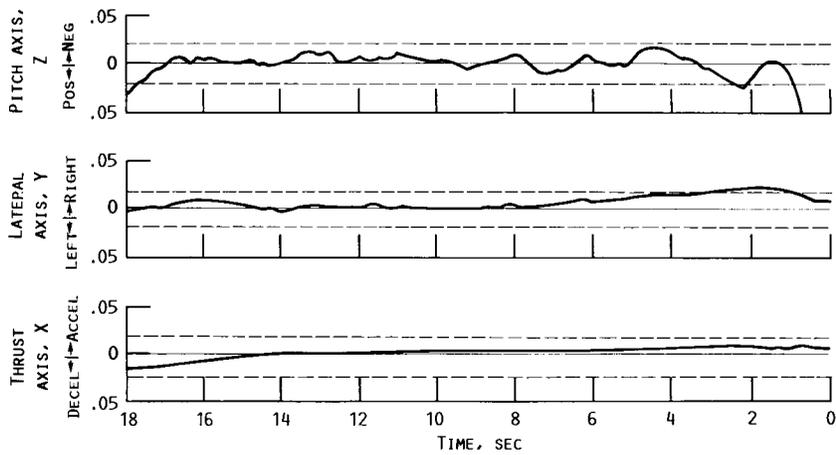


FIGURE 10.- BETTER-THAN-AVERAGE TRAJECTORY. TRAJECTORY 6; FLIGHT DATE, MAY 22, 1986.

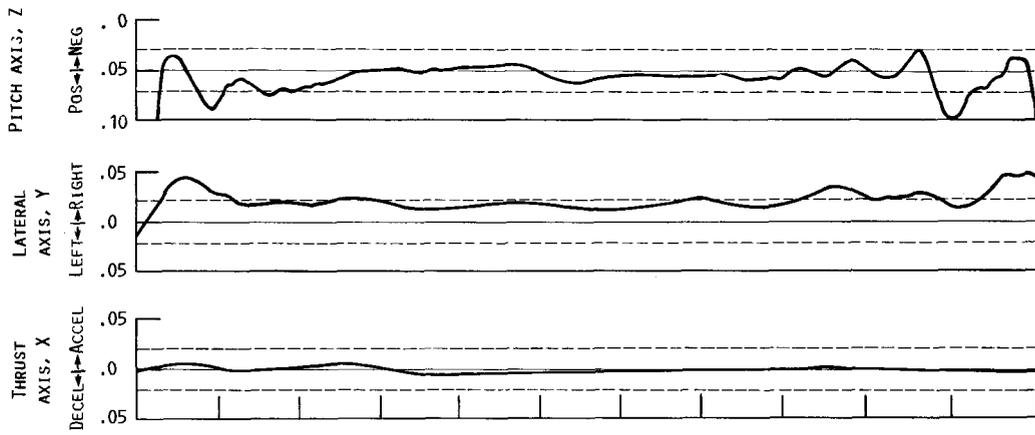


FIGURE 11.- FRACTIONAL g (1/20g) TRAJECTORY. TRAJECTORY 7; FLIGHT DATE, OCTOBER 3, 1985.

1. Report No. NASA TM-87358		2. Government Accession No.		3. Recipient's Catalog No.	
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16. Abstract <p>This report describes the features, design, calibration, and testing of Lewis Research Center's new acceleration display system for aircraft zero-gravity research. Specific circuit schematics and system specifications are included as well as representative data traces from flown trajectories. Other observations learned from developing and using this system are mentioned where appropriate. The system, now a permanent part of Lewis's Learjet zero-gravity program, provides legible, concise, and necessary guidance information enabling the pilots to routinely fly accurate zero-gravity trajectories. Regular use of this system resulted in improvements of the Learjet zero-gravity flight techniques, including a technique to minimize lateral accelerations. Lewis's Gates Learjet trajectory data show that accelerations can be reliably sustained within 0.01g for 5 consecutive seconds, within 0.02g for 7 consecutive seconds, and within 0.04g for up to 20 seconds. Lewis followed the past practices of acceleration measurement, yet focussed on the accelerations displays. The principal change was the conversion of the usual needle meter displays to LED bar graph displays positioned and aligned with their respective flight controls. Refinements based on flight experience included evolving the ranges, resolutions, and frequency responses to fit the pilot and Learjet responses. A bias feature, which allows fractional g trajectories to be flown, and the practice of regularly recording flight performance also became features of the new Lewis system.</p>					
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