RELATIVE EFFECTS OF ROLL AND YAW MOTION CUES IN MANUAL CONTROL

by

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ABSTRACT

Experiments were performed to determine the relative contributions of otoliths and semicircular canals to manual control of difficult (K/s^2) vehicle dynamics. Motion cues (yaw and roll) were provided to subjects with head orientations carefully specified such that in one case semicircular canals only were stimulated, whereas in the second case the otoliths as well as the same semicircular canals were stimulated. Human operator describing functions were measured and compared for the two cases. High frequency human operator amplitude ratio was greater when both otoliths and semicircular canals were stimulated than when only semicircular canals were stimulated.

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CHAPTER I

INTRODUCTION

1.1 The Vestibular System

In several hundred million years of evolution, man's nonvisual equilibrium sensors have changed but little. Our vestibular apparatus is a hand-me-down from the early jawed vertebrates. Those vertebrates were fish, evolving midway in the Paleozoic Era, and the vestibular apparatus developed then served them in essentially the same manner in which it now serves us.[1] Teleologically it is not surprising that evolution of the vestibular apparatus proceeded very slowly once early development occurred. Motion sensation is a general function, and the sensory requirements have been similar among most vertebrates and have not radically changed with time. However, the vestibular system seems to be of less importance to man than to other contemporary mammals, such as the monkey and the cat.[2]

The advent of man-made transportation devices capable of sustained velocities and accelerations brought vestibular apparatus function into question. Early anatomists described the vestibular apparatus morphologically in great detail. Modern histological and cytological techniques, including electron microscopy have added to the quantity of anatomical and physiological information describing the system and how it works. A brief simplified description follows; for more details, see reference 3.

The vestibular apparatus is located in each inner ear. It has no role in auditory sensation. There are two sub-organs in the vestibular system which are of primary interest, the semicircular canals and the utricular and saccular otoliths.

Each set of semicircular canals is a system composed of three nearly orthogonal bony circular ducts (Fig. 1.1) containing flexible tubes which are filled with a fluid called endolymph. Each canal originates from a common sac, the utricle, forms a rough semicircle, and returns to the utricle. Displacement of a "cupula" by endolymph motion inside each canal causes increased nerve firings which are relayed to the central nervous system via the vestibular nucleus. The operation of each semicircular canal has been modelled with some success, as the mechanical action of an overdamped torsion pendulum.[4] Analysis has shown that the semicircular canals function as angular velocity sensors over much of the physiological frequency range.

The utricular otolith is shown schematically in Fig. 1.2. The gelatinous mass labeled "otolith" contains calcium carbonate granules, making it denser than the surrounding fluid. The otolith is supported by hairs and sensory cells from the macula, which allow sliding travel of approximately 0.1 mm. The motion and consequent

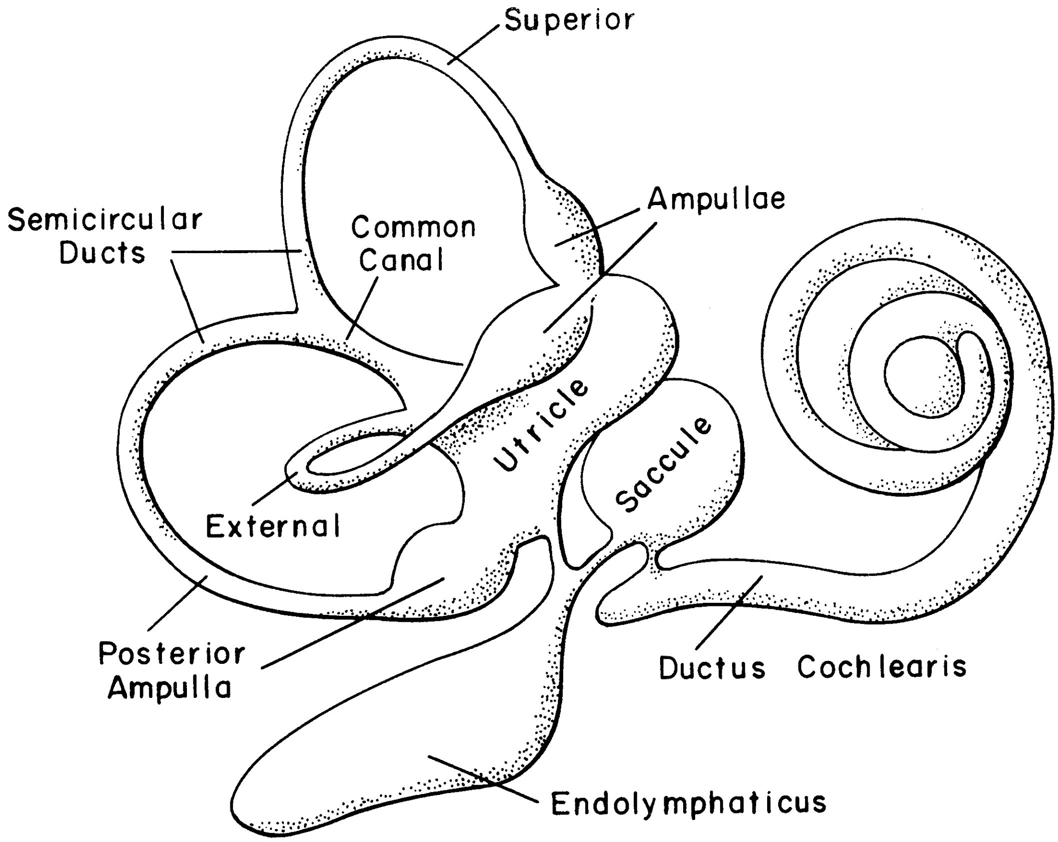


Figure 1.1 The vestibular apparatus (from Meiry, cited from J. H. Barnhill, Surgical Anatomy of the Head and Neck, The Williams and Wilkins Co., Baltimore, 1940)

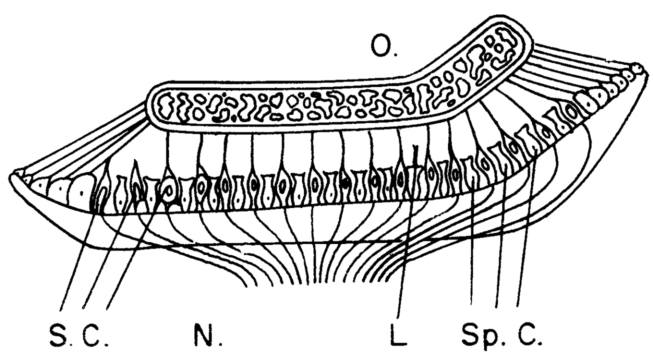


Fig. 2.2 Schematic Drawing of a Cross Section of an Otolith and its Macula. O. is the Otolith, Suspended by Strands which Run from the Margins to the Macula, Consisting of Supporting Cells (Sp.c.) and Sensory Cells S.C. Between the Otolith and the Macula There is a Thin Layer (L) to Allow the Otolith to Slide Over the Macula. N. is the Nerve (from Meiry, cited from J. J. Groen, "The Semicircular Canal System of the Organs of Equilibrium," Physics in Medicine and Biology, 1, 1956-57).

distortion of sensory cells causes neural firing which is transmitted to the brain, again via the vestibular nucleus. Because of its density, the otolith is displaced by inertial reaction forces. The sensing mechanism is probably the bending of the hair cells, so that the otolith is primarily responsive to shear components of force defined with respect to the principal plane of the otolith, although compressive forces may also be sensed. The saccular otolith is not clearly understood. It is located in a plane nearly perpendicular to the utricular plane and has histological structure identical to that of the utricular otolith.

It is generally agreed that the semicircular canals sense angular velocity and that the otoliths sense linear acceleration and tilt, or more appropriately, specific force, where specific force is the vector sum of the gravity vector and other accelerations.

1.2 General Methods of Research

Research has been done in recent years in attempts to describe the dynamic sensing characteristics of the semicircular canals and otoliths in control engineering terms. Models have been postulated on the basis of experimental findings from four kinds of work:

1. physiological observations.
2. biophysical evaluations of properties of the system components.

3. nystagmus recordings.*

4. subjective indication of sensed orientation.

The third method involves measurement of a signal which has been processed by the motor cortex area of the brain and also by eye effector muscles. The fourth method is even further removed from direct vestibular output. In this case the vestibular signal is processed by motor cortex as well as conscious centers of the cerebrum and then also by effector mechanisms (e.g. muscle) which indicate the sensed quantity (motion and orientation) to an observer.

Very little is known or even conjectured concerning central nervous system processing of signals input from the periphery. This is obviously a difficult problem because of the brain's complexity. There are two avenues to complete knowledge of brain function. The first requires a complete "circuit diagram" of the brain with its uncountable synapses. The second requires a near-infinite number of input-output experiments to cover all possible inputs and outputs. Neurophysiologists attack the problem using both methods. Their work is done using sophisticated dissection, transection, and microscopy techniques on localized areas of the brain. Engineers approach biological systems from an intact organism input-output view. They

* These are recordings of eye movements in response to head motion. Because the vestibular system determines eye velocity as the head moves, these data are taken as "objective" indications of vestibular output.

are generally interested in total system performance rather than each subsystem's performance.

1.3 The Problem

Much of the research done on human vestibular system response has involved complex motions, such as encountered flying an aircraft. This yielded valuable insight into an overall description of pilot capability. However, in interpreting these results, a number of investigators have explicitly assumed that perception of angular rotation is attributable only to the semicircular canals. McRuer et al[5] state that semicircular canals alone aid pilot equilization in attitude control of aircraft flying straight and level. They indicate that otoliths have an unimportant role in this task. Stapleford,[6] on the basis of unexplained experiments claims, "The utricular (otolith) path will not be used unless the linear acceleration feedback is more favorable than the semicircular canal feedback."

On the basis of nystagmus recordings and consideration of otolith structure, it appears that these statements oversimplify otolith function. Lowenstein says "(there is) . . . no reason why an otolith should not respond to angular acceleration . . ."[7] Otolith effects on vestibular nystagmus in pure angular rotation have been investigated,[8,9] and the results are summarized by Young.[10] His conclusion is that otolith output adds vectorially to semicircular canal output to produce a modified nystagmus.

It is known that motion cues aid in manual vehicle control by enabling the human operator to increase his phase lead and gain at high frequencies. Shirley (ref. 11) provided the human operator with roll motion cues, which stimulated both the semicircular canals and the otoliths. Otolith stimulation occurred because of changing head orientation with respect to the vertical. The relative contributions of semicircular canals and otoliths to perception of angular rotation is unknown.

1.4 The Goal

This thesis will try to separate semicircular canal and otolith contributions to vehicle control. This is approached by investigating the interaction and integration of semicircular canal output and otolith output. These efforts are justified by several possible applications:

1. The results may be useful in determining the relative importance of linear and angular motion cues in moving base simulators.
2. Long space missions may have some effects on otolith function because of the loss of Earth's constant one-g force field. If otolith functions were completely lost, or impaired, it would be helpful to know the effects beforehand.
3. The effects of applying an artificial gravity for long space flights could be more accurately predicted.
4. The research extends basic knowledge of man's physical characteristics.

1.5 The Method and Results

The experimental procedure attempted to separate semicircular canal and otolith contribution to perception of angular rotation. This was accomplished by rotation of subjects in a moving base simulator. In each of two cases the plane of rotation corresponded to the head frontal plane, but in the first case (yaw) the head was on the rotation axis, and in the second case (roll) the head was approximately two feet off the rotation axis. This gave rise to identical semicircular canal stimulation in each case. No otolith stimulation occurred in the first case. Changing head position with respect to gravity stimulated the otoliths in the second case.

Comparison of results of these experiments should tell us how otolith and semicircular canal output are integrated, as well as give an accurate indication of semicircular canal sensing capabilities.

Using methods developed by McRuer et al[16] and adapted to the Man-Vehicle Laboratory hybrid computer-simulator facility by Richard Shirley, data were obtained for the human operator's gain and phase when:

1. semicircular canals only were stimulated.
2. semicircular canals and otoliths were stimulated.

This involved approximations, the nature of which are discussed subsequently. Results obtained show that addition of otolith stimulation to semicircular canal stimulation allows the human operator to increase his gain and phase lead over the middle and high frequency range. For summary and conclusions, see Chapter V.

CHAPTER II

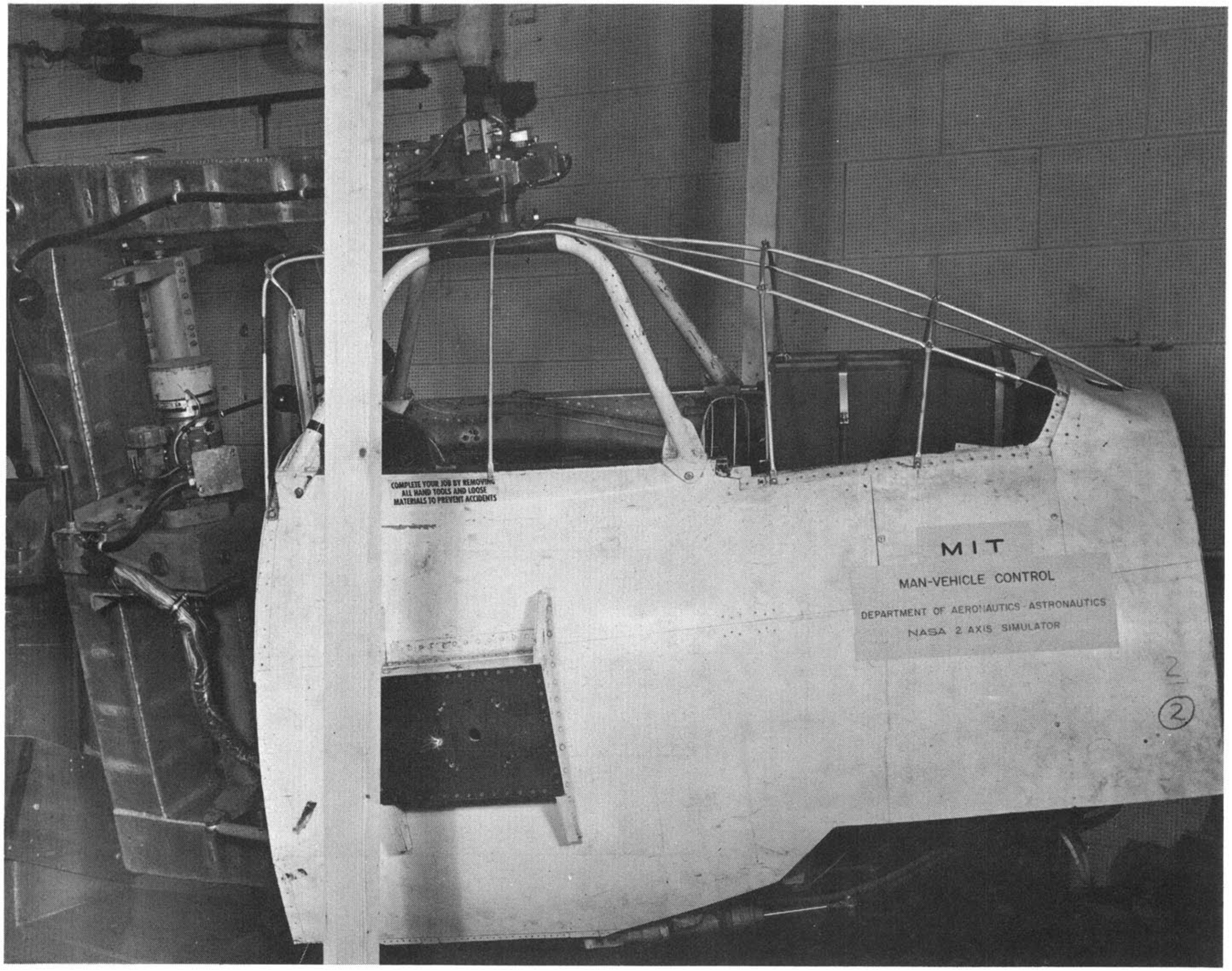
THE EXPERIMENTAL METHOD

2.1 Head Position

In order to isolate the effects of semicircular canals and otoliths, one requires stimulation of the semicircular canals without causing otolith stimulation. Since the otoliths respond to specific force, one can obtain a constant output from them by applying a constant specific force. It would be desirable to apply zero specific force for observation of pure canal response, and this could be accomplished in a weightless environment. Since such an environment is available only at very great expense, the alternative is to provide conditions that keep the specific force direction and magnitude constant during tests of the semicircular canals. We would expect the constant bias signal of the otoliths to contain no information and have no effect. Experiments were performed rotating seated (upright) subject about a vertical axis passing through the middle of their heads (hereafter YAW FHU for yaw, fixed-head-up). With this arrangement each otolith received small tangential accelerations and very small equal and opposite components of centrifugal force. To determine the effect of otolith output on motion response while stimulating the semicircular canals in the same plane as above, the subject was rotated about a horizontal axis with head fixed ninety degrees forward of normal upright posture, i.e., looking at the floor (ROLL FHD for roll, fixed-head-down). The motivation for this rather grotesque posture was to orient the canals with respect to motion exactly as in YAW FHU. Since canal stimulation is identical in the two cases, any difference in response could only be due to the effect of otolith input and possible other factors such as awkward position, which will be discussed. To check results obtained from the experiments described, one could perform a dual set of experiments, YAW FHD (YAW, fixed-head-down) and ROLL FHU (ROLL, fixed-head-up). Here again the canals are oriented identically with respect to the motion in both cases, and if assumptions are correct, the experimental sets should give similar results for the effects of otolith stimulation on motion response. Both experiments were performed and results will be compared in Chapter V.

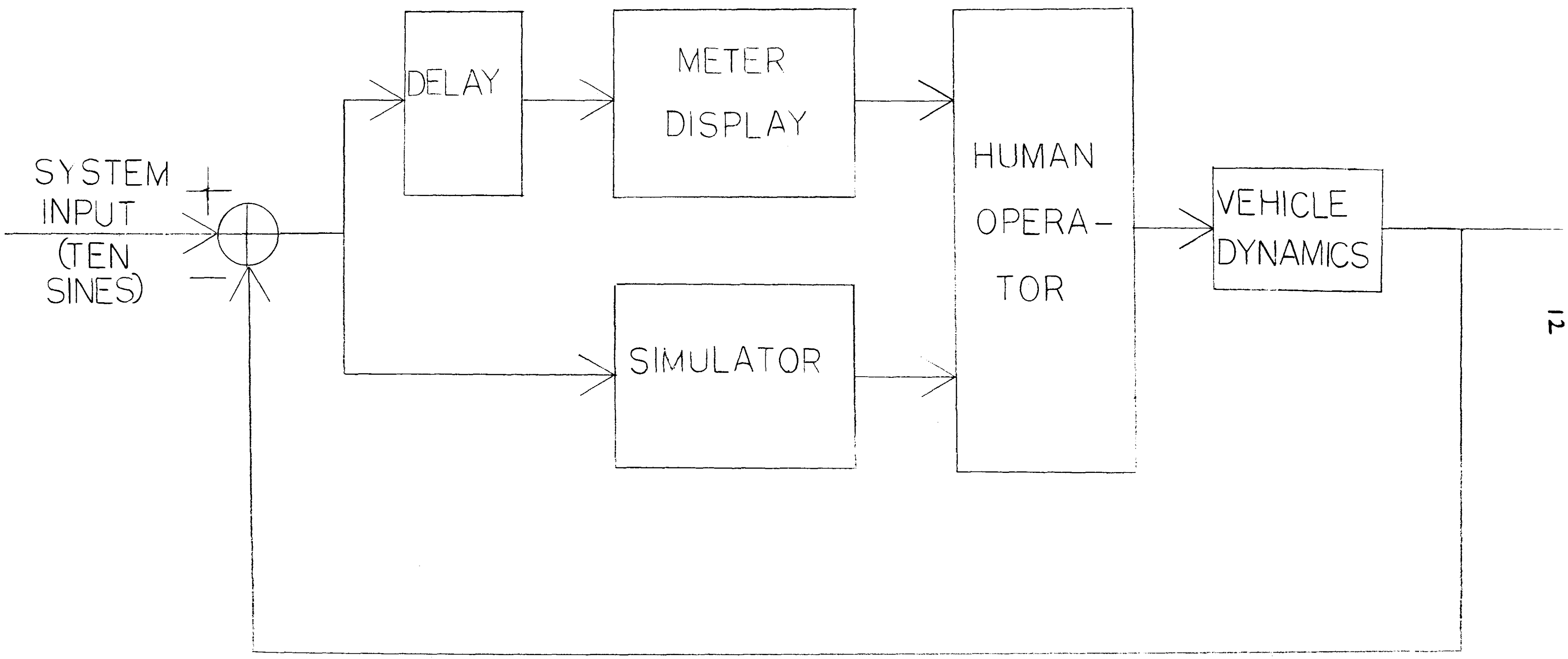
2.2 The Motion Cues

Rotational motion cues were provided by the M.I.T. Man-Vehicle Laboratory NE-2 two degrees of rotational freedom simulator built by NASA Ames (Fig. 2.1). A pseudo-random input made up of the sum of ten sine functions at frequencies from w_1 = .14 rad/sec to w_{10} = 7.7 rad/sec was supplied to the system (Fig. 2.2) in which the human operator was controller. Subjective indication of orientation was obtained by providing the subject with a



The NE-2 simulator used in the experiment

Figure 2.1



SYSTEM DIAGRAM

Figure 2.2

stick with which to control the simulator. The stick output was input to the analog computer simulated vehicle dynamics, Y_c. The output of the vehicle dynamics was compared to the system input to generate an error signal. The error signal in turn drove the D.C. position servomotors of the simulator. Thus the error was displayed to the subject as motion about a reference point (in roll the reference was the vertical, and in yaw the reference was due east) and as a pointer deflection on a D.C. voltmeter.

2.3 The Visual Cues

Visual cues were confined to the D.C. voltmeter display, as the cab was covered with an opaque material to eliminate external cues. The subjects kept their eyes open and the inside of the cab was dimly lighted. The question naturally arises as to why use visual information at all. Although in roll, motion cues alone enable one to maintain a laboratory vertical reference to quite good accuracy, no true internal reference is available in yaw. A subjective reference does exist in the absence of visual or other non-motion cues, but the subjective reference shifts away from a laboratory reference fairly rapidly. The direction and rate of reference shift in yaw varies with individuals, but the rate is typically one to two degrees per second. The run length used was two minutes, and the simulator operating range in yaw was plus or minus forty degrees. Clearly a run could rarely be finished before the simulator hit the limit stops, unless visual reference cues were provided. It has been shown by Meiry[12] and others[13] that the human operator makes better use of motion cues than visual cues at high frequencies (Fig. 2.3). It was reasoned that by making the visual information identical in both roll and yaw, differences in performance at high frequencies would be observable because of reliance on vestibular information. The ultimate justification of this approach is the data obtained, which did show statistically significant differences between the two situations. Data were taken for runs in ROLL FHD and ROLL FHU, both with motion cues only, to tie in with Shirley's data. Results are compared in section 4.6.

2.4 Tactile Cues and Muscle Proprioceptors

Great care was taken to make ROLL FHD provide the same cues to the subject as YAW FHU (except for otolith stimulation in ROLL FHD), and similarly for ROLL FHU and YAW FHD. Success was achieved except in two areas. Differences in tactile sensations and muscle proprioceptors were impossible to eliminate. The subjects were securely strapped in the aircraft seat so that maximum travel in any direction except for extremities was approximately one inch. Subjects' heads were securely fixed relative to the simulator cab with an adjustable baseball catcher's mask. This eliminated the neck proprioceptors, but arms, legs, and shoulders received quite different force distributions in roll and in yaw. However, physiological considerations seem to indicate that tactile cues may not be very important. A good deal of research has been done into the action

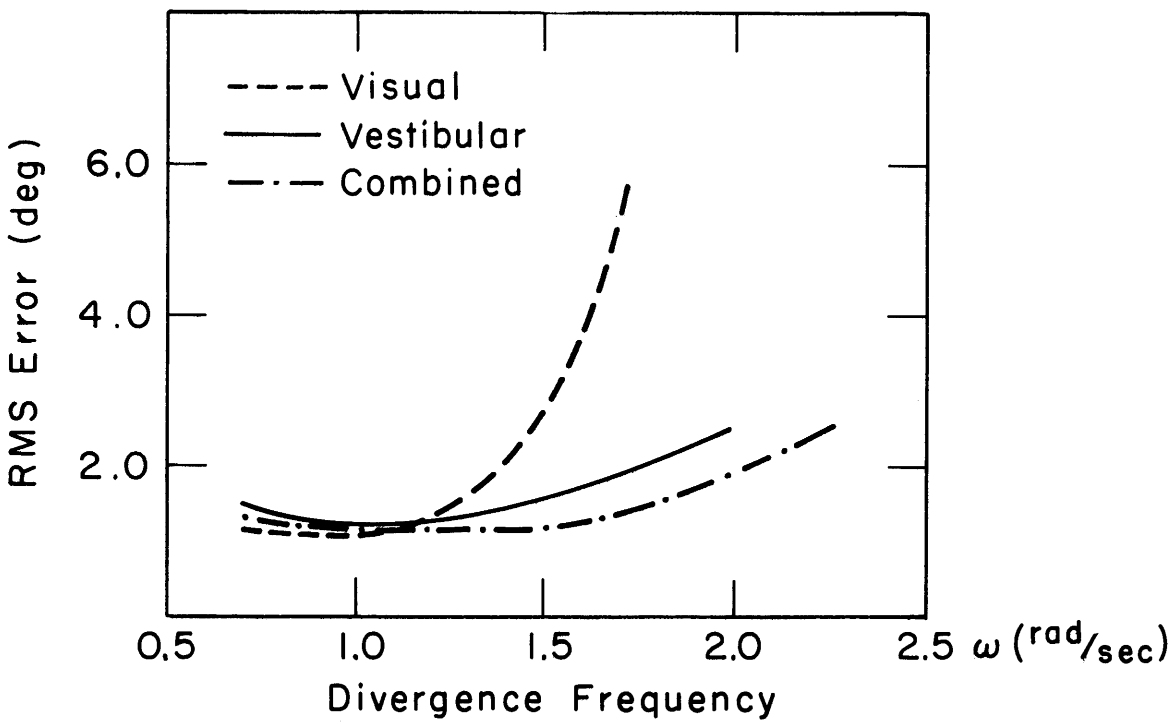


Figure 2.3 RMS Error for control of inverted pendulum (from Meiry, ref. 12)

of "mechanoreceptors," as tactile sensors are known.[14] These sensors are individually binary (on-off) devices but collectively transmit magnitude information by relative numbers of receptor firings. Crucial to perceived sensation is central nervous system processing of the tactile input. Considerations of the complexity of a processor that could decode information from all parts of the body and yield useful information about complex motions lead one to the conclusion that tactile information might be useful only for simple large magnitude motions. Young and Graybiel,[15] however, found that labyrinthine defective subjects made surprisingly good use of motion cues in vehicle control. Since visual and vestibular cues were not available, tactile cues were presumably useful. One must simply conclude that little is known about tactile effects.

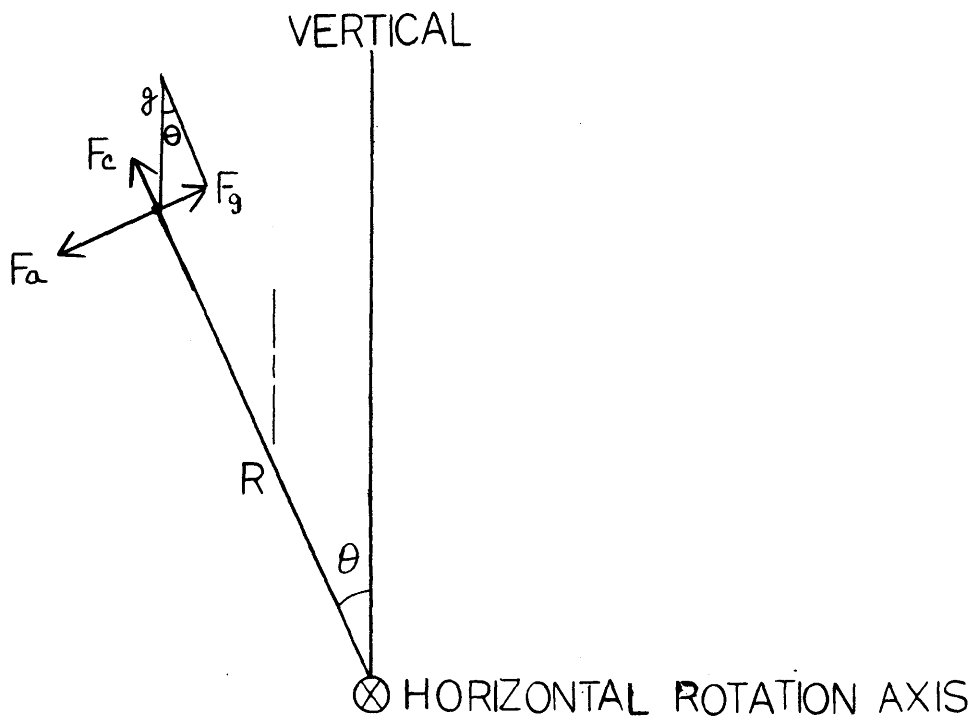
2.5 Posture

The effect of an unnatural posture in the FHD position is difficult to evaluate. It was primarily this last which prompted the ROLL FHU versus YAW FHD experiments, in which the postural variable is working in yaw rather than in roll. Another related difficulty arose from the inflexibility of the simulator seat and the human skeleton. These two factors combined to make it impossible for subjects SU and BP to position their heads closer than about eight inches from the yaw rotation axis when in the FHD position. The other two subjects were able to position their heads on the yaw axis.

Because head position was off the roll axis (two feet) in ROLL FHD and ROLL FHU, and off the yaw axis (eight inches) for two subjects in YAW FHD, an analysis of variations in specific force with head position is in order. Figure 2.4 shows the three forces and their root mean square values over the input for R = 2 feet and R = 8 inches. F_c can be neglected for either R, since it is below otolith threshold (.005 g). For R = 8 inches, $F_a \cong .12\ F_g$, which is well above otolith threshold. It would be expected, then, that results for subjects SU and BP in YAW FHD might show effects of otolith stimulation not shown in YAW FHU. This did occur as will be pointed out in section 4.4.

2.6 Experimental Apparatus

Data were taken over a ninety second period after thirty seconds of warmup time for each run. The input (sum of ten sines), calculated and stored on magnetic tape, was supplied to the system by the computer. The hybrid computer is a GPS Corp. 290T which interfaces the GPS analog portion with a Digital Equipment Corporation PDP-8 (Fig. 2.5). The error signal and vehicle dynamics output were sampled by the computer every 0.1 seconds. The NT-2 simulator has frequency response over the range .02 to 1 cps closely approximating a pure delay of 0.1 seconds. A D.C. voltmeter was used to display the error rather than an oscilloscope because of the ease with which the meter could be relocated for various head positions. The voltmeter (Weston model 643) was specially modified for this



F'_c = RMS centripetal force

F'_a = RMS tangential accelerative force

F'_g = RMS shear component of gravity

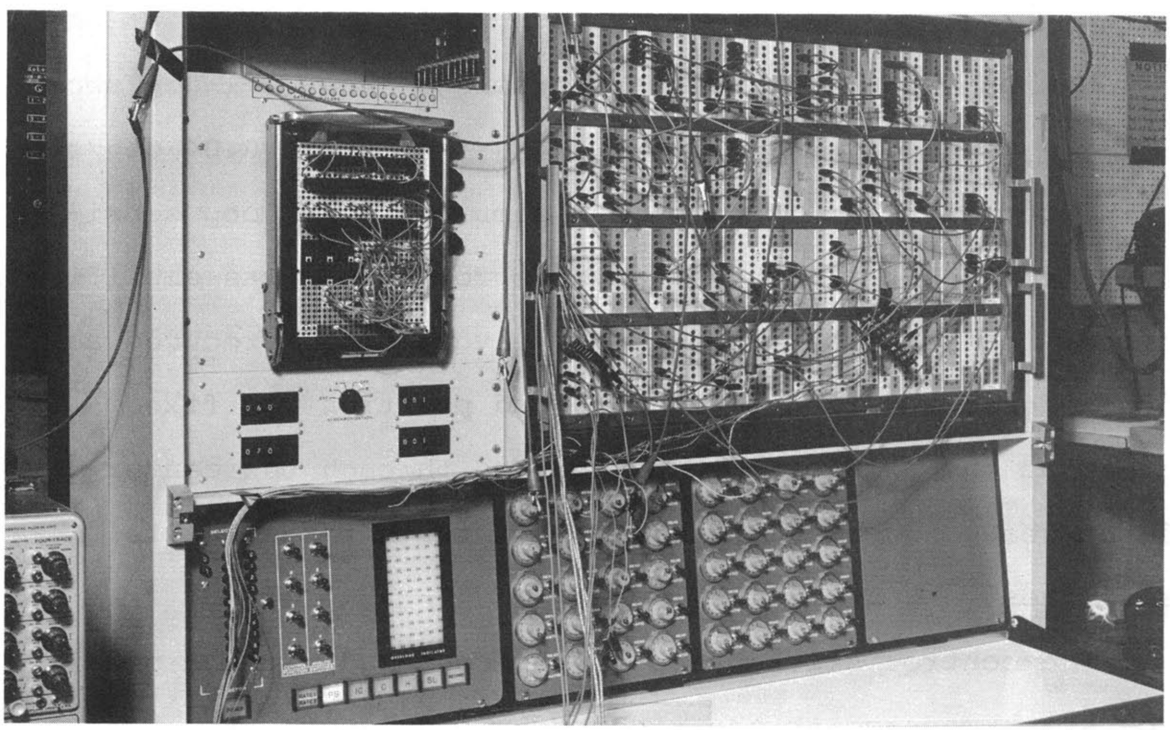
$$F'_c = R\,\overline{(\dot{\theta})^2} \cong \begin{cases} .0005\text{ g for R} = 2/3\text{ ft.} \\ .0015\text{ g for R} = 2\text{ ft.} \end{cases}$$

$$F'_a = R\,\overline{(\ddot{\theta})^2} \cong \begin{cases} .017\text{ g for R} = 2/3\text{ ft.} \\ .051\text{ g for R} = 2\text{ ft.} \end{cases}$$

$$F'_g \cong g\,\overline{(\theta^2)}^{1/2} \cong 0.139\text{ g}$$

Figure 2.4
Components of Specific Force at the Otolith

GPS 290T Hybrid Computer, Digital Portion



GPS 290T Hybrid Computer, Analog Portion

Fig. 2.5

display. Meter deflection was linear over the entire range of plus or minus ten volts, which corresponded to deflections of plus or minus two inches from the null reading. The meter frequency response approximated a 0.04 second delay over the range 0.02 to 1.0 cps. To obtain a 0.1 second delay in the visual loop to match the motion delay, the error signal was delayed in the digital computer for 0.06 seconds and at the meter for 0.04 seconds.

The dynamic characteristics of the NE-2 simulator are:

Maximum rotation: Yaw, ±35°
Roll, ±360°

Maximum angular velocity: Yaw, 2 rad/sec
Roll, 8 rad/sec

Maximum angular acceleration: Yaw, 10 rad/sec^2
Roll, 15 rad/sec^2

Maximum angular acceleration noise: Yaw, 0.1 deg/sec^2
Roll, 0.04 deg/sec^2

Care was taken to match the simulator yaw loop sensitivity to the roll loop. The yaw error signal was amplified so that for both roll and yaw a one volt error produced a three degree rotation. In yaw, head position was fixed such that the axis of rotation passed through the center of the head. The roll axis passed through the subjects' belt lines.

The control stick was a spring-centered, linear pencil-type stick mounted to the right of the subject. The control stick output was kept constant at plus or minus 100 volts, corresponding to the plus or minus thirty degree maximum stick travel. Control stick motions were left and right for left roll (or left yaw) and right roll (or right yaw).

Vehicle dynamics were simulated on the analog computer. Subject training was started with $Y_c(s) = K/s(s + 1)$ where K actually represents stick gain. Dynamics were increased in difficulty, as training progressed, to $100/s^2$. Data were taken only for $Y_c(s) = 100/s^2$. This $Y_c(s)$ is the relationship between control moment and angular position of a spacecraft in the absence of atmosphere. This particular system was chosen in light of Shirley's conclusions that high gain, marginally stable vehicles enable the operator to utilize motion cues very effectively.

2.7 Subjects

Subjects were strapped to the seat with over-the-shoulder harnesses and a lap belt. Foam rubber cushions under and behind the subject were used for comfort and to attempt to minimize tactile cues. When the head was fixed in place it was supported by a strap to the catcher's mask to avoid neck muscle strain.

Four subjects were used, each of whom had extensive previous experience (in roll only) in the same simulator. The subjects were:

SU: a male M.I.T. undergraduate.

JG: a male M.I.T. undergraduate.

BP: a female M.I.T. undergraduate.

TI: a male M.I.T. undergraduate with a commercial pilot's license.

Because of their experience, the subjects needed little practice to reach consistent levels of performance (six hours average). The final level of performance varied considerably among the subjects, but in each case consistency was achieved. Data taking was confined to two three-hour sessions for each subject. The sessions included warmup runs to check performance against former levels. No fatigue was noticed in the three hour period, probably because subjects had five minutes to rest between each two minute run. The subjects were told their scores (integral squared error - ISE - see section 3.1) after each run to provide incentive for high performance. Inter-subject competition was not encouraged and did not develop significantly. The subjects seemed to enjoy the runs and were definitely motivated to improve their scores. Four situations were tested five times each, for each subject. These were: ROLL and YAW FHU, and ROLL and YAW FHD. The situations were presented to the subject in a random order to eliminate habituation effects.

The subjects were very vocal about how a new situation affected them. One comment made independently by each subject concerned the difficulty of "seeing" the display in ROLL FHD. In this situation the meter was at their feet and the axis of rotation was approximately mid-way between meter and eyes. Moving the meter to a position on the axis did not help. A possible explanation is that the otolith "tells" the eye muscles to change the focus of the lens, since the head is apparently undergoing an acceleration away from the object focused on. Another curious incident occurred at the beginning of the experiment, when the first subject was first rotated in yaw. Motion cues were unwittingly set opposite stick displacement and the visual display. The subject controlled $Y_c(s) = 50/s(s + 1)$ with high ISE. He complained of slight nausea, difficulty in focusing on the meter, and general but vague discomfort. Reversing the motion caused all trouble to disappear. These were symptoms of vestibular-visual confusion.

CHAPTER III

THE MEASUREMENTS

3.1 Data Taken by the Computer

The measurement techniques used for this experiment were developed by McRuer et al[16] and modified for the M.I.T. Man-Vehicle Laboratory facilities by Shirley. Shirley wrote the PAL III computer programs that supply the system input and take data at the human operator's input (system error) and output (control stick). These parts of Shirley's programs, his "input" and "run" routines, were essentially unaltered.* Some changes were made in data reduction, however. The general scheme of the measurement process is outlined here; for more details see ref. 11.

The system input is given by:

$$i(t) = \sum_{k=1}^{10} A_k \sin(w_k t + t_o)$$

where the w_k in rad/sec are:

$w_1 = .1405$	$w_4 = .6326$	$w_7 = 2.1787$
$w_2 = .2108$	$w_5 = .9137$	$w_8 = 2.8816$
$w_3 = .3512$	$w_6 = 1.4757$	$w_9 = 4.2872$
		$w_{10} = 7.6605$

* The delay written into Shirley's program was changed from 0.1 sec to 0.06 sec.

$$A_1 = A_3 = A_5 = A_7 = +1.0$$

$$A_2 = A_4 = A_6 = -1.0$$

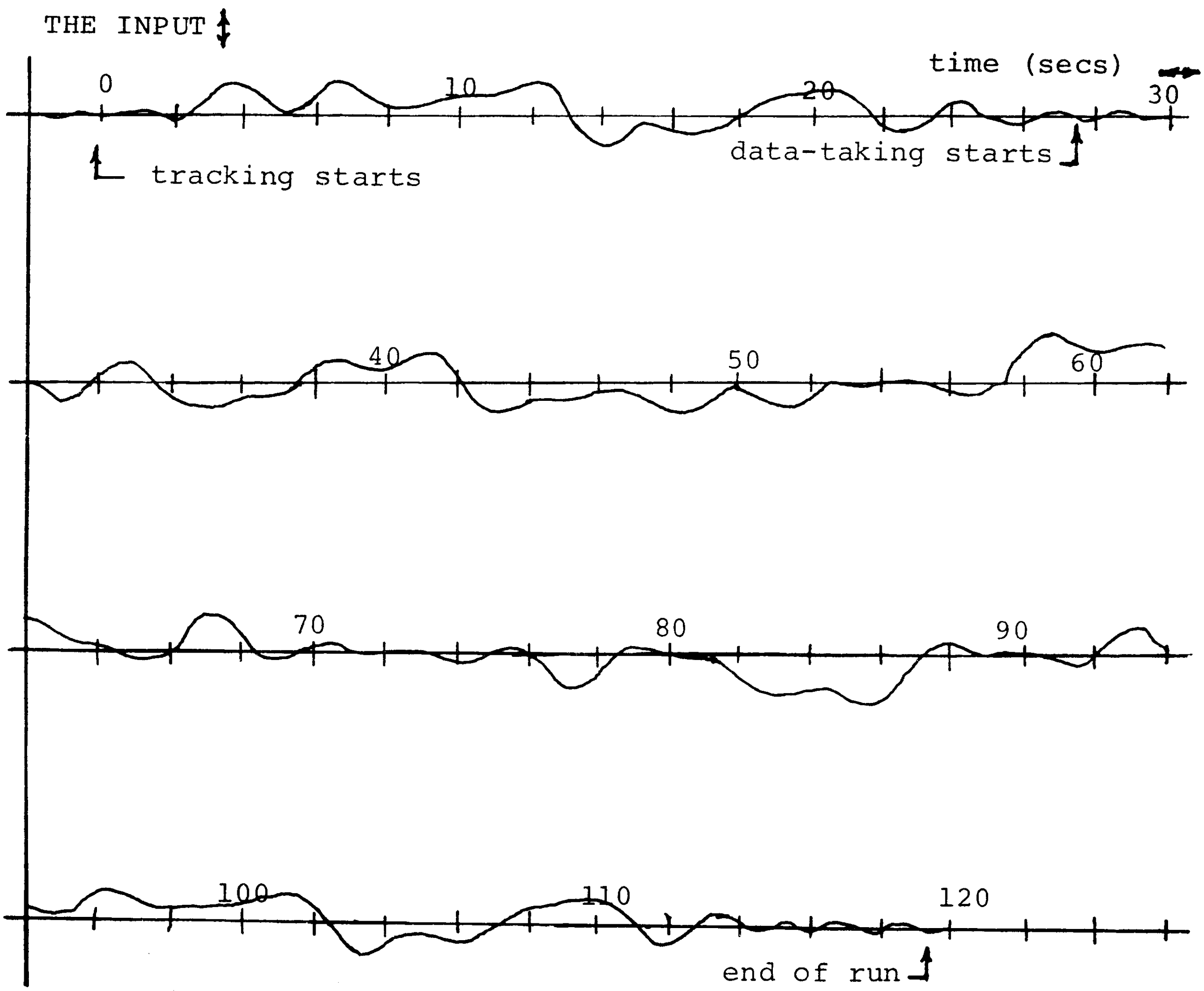
$$A_8 = A_{10} = -0.1$$

$$A_9 = +0.1$$

$$t_o = -28 \text{ sec}$$

The A_k's were chosen with alternate signs to avoid a large initial transient. The high frequencies were attenuated ($A_k = \pm 0.1$) to make the task easier for the subject. t_o is warm-up time, chosen such that $i(t_o) = 0$. The input was produced every .02 seconds, so that it appeared continuous. Figure 3.1 shows the input.

The error voltage and vehicle dynamics output voltage were sampled every 0.1 second. Because measurements were taken at the vehicle dynamics output, $Y_pY_c(s)$ was obtained rather than $Y_p(s)$. This was done to avoid the difficulty of measuring the low level signals for low frequency output of the human operator. Shirley's measurements were taken at the human operator input, and hence his analytical derivations are modified below. The data taking period was 89.6 seconds, producing 896 samples of each signal during a run. The system error was squared and integrated over the data period, and it was converted to a digital number at the end of the run. This gives the integral squared error (ISE), a measure of average performance over the run. When this number is compared to the integral squared input, the



THE INPUT

Above is a tracing of the input which is not precise, but which gives an excellent indication of the nature of the input which is the sum of ten sines.

Figure 3.1

relative integral squared error (rISE) is obtained. This is a ratio of total error power to total input power.

3.2 Data Processing

The data were processed after each run by the computer. With reference to Fig. 3.2, the following quantities were available to the computer for computations:

1. $e(n\Delta t)$, the input to the human operator which is also the system error
2. $M(n\Delta t)$, the output from the vehicle dynamics
3. $\sin(w_k n\Delta t)$ and $\cos(w_k n\Delta t)$ for each of the ten frequencies of the system input
4. $\sin(w_j n\Delta t)$ and $\cos(w_j n\Delta t)$ for each of ten w_j's between the w_k's of the input

where the w_j's were .0702, .2810, .4920, .7732, 1.1947, 1.8977, 2.6004, 4.0060, 5.5523, and 9.6288 rad/sec. $\Delta t = 0.1$ sec.

The data were processed as follows:

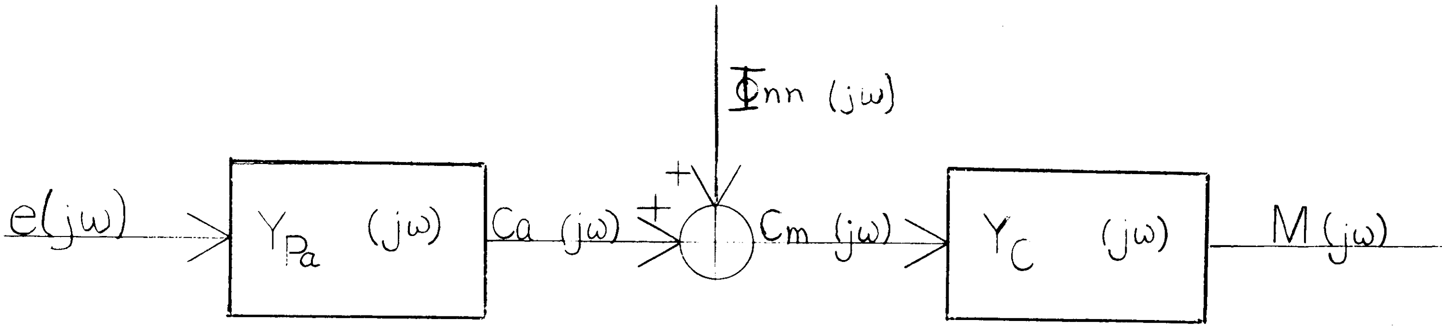
$$A_{ek} = \sum_{n=1}^{896} e(n\Delta t)\ \sin(w_k n\Delta t)$$

$$B_{ek} = \sum_{n=1}^{896} e(n\Delta t)\ \cos(w_k n\Delta t)$$

$$A_{mk} = \sum_{n=1}^{896} M(n\Delta t)\ \sin(w_k n\Delta t)$$

$$B_{mk} = \sum_{n=1}^{896} M(n\Delta t)\ \cos(w_k n\Delta t)$$

$$A_{mj} = \sum_{n=1}^{896} M(n\Delta t)\ \sin(w_j n\Delta t)$$



e(jw) = the input to the human operator

Y_{pa}(jw) = the human operator's describing function relating C_a(jw) to e(w)

C_a(jw) = the human operator's output linearly correlated with his input

Φ_{nn}(jw) = the power spectral density of the human operator's output uncorrelated with his input

C_m(jw) = the total human operator output

Y_c(jw) = the vehicle dynamics

M(jw) = the vehicle dynamics output

Figure 3.2
The Model for the Human Operator

$$B_{mj} = \sum_{n=1}^{896} M(n\Delta t)\ \cos(w_j n\Delta t)$$

These data were used to compute the human operator describing function $[Y_p(jw)]$ and remnant as follows:

$$|e(w_k)|^2 = (A_{ek}^2 + B_{ek}^2)(\Delta t)^2 \tag{3.1}$$

$$\underline{/e(w_k)} = \tan^{-1}\left(\frac{B_{ek}}{A_{ek}}\right) \tag{3.2}$$

$$|M(w_k)|^2 = (A_{mk}^2 + B_{mk}^2)(\Delta t)^2 \tag{3.3}$$

$$\underline{/M(w_k)} = \tan^{-1}\left(\frac{B_{mk}}{A_{mk}}\right) \tag{3.4}$$

$$|M_{nn}(w_j)|^2 = (A_{mj}^2 + B_{mj}^2)(\Delta t)^2 \tag{3.5}$$

Equations 3.1 and 3.2 give the amplitude and phase of the human operator input. Equations 3.3 and 3.4 give the amplitude and phase of the vehicle dynamics output. The combined describing function is

$$|Y_p Y_c(w_k)|^2 = \frac{|M(w_k)|^2}{|e(w_k)|^2} \tag{3.6}$$

$$\underline{/Y_p Y_c(w_k)} = \underline{/M(w_k)} - \underline{/e(w_k)} \tag{3.7}$$

3.3 The Remnant Correction

Equation 3.5 gives a measure of the magnitude of the remnant as passed through Y_c. Since the remnant is fed back through the system dynamics, the error is affected. Hence we must correct $Y_pY_c(w_k)$ for the effect of the remnant. The remnant is a random signal possessing no fixed phase,[16] so we need not correct $\angle Y_pY_c(w_k)$. Referring to Fig. 3.2, the calculations for the remnant corrected $|Y_pY_c(w_k)|$ follow:

$$Y_{pa}(w) = \frac{C_a(w)}{e(w)} = \text{the actual human operator's describing function} \tag{3.8}$$

$$Y_{pm}(w) = \frac{M(w)}{Y_c(w)e(w)} = \text{the measured human operator's describing function} \tag{3.9}$$

$$F_{xm}(w) = \frac{Y_c(w)}{1 + Y_{pa}(w)Y_c(w)} = \text{the transfer function between x and M} \tag{3.10}$$

$$F_{xe}(w) = \frac{-Y_c(w)}{1 + Y_{pa}(w)Y_c(w)} = \text{the transfer function between x and e} \tag{3.11}$$

Following Shirley's derivation in ref. 11,

$$\frac{|M(w_k)|^2}{(\Delta t)^2} = A_{ek}^2 \; |Y_{pa}(w_k)Y_c(w_k)|^2 + \Phi_{nn}(w_k)\,\delta w_k |F_{xm}(w_k)|^2 \tag{3.12}$$

and

$$\frac{|e(w_k)|^2}{(\Delta t)^2} = A_{ek}^2 + \Phi_{nn}(w_k) \; \delta w_k |F_{xe}(w_k)|^2 \tag{3.13}$$

where A_{ek} is the amplitude of the sinusoid of frequency w_k at e due to the input, i(t), and δw_k is a bandpass measure (see ref. 11). It follows from eq. 3.9, 3.12, and 3.13 that

$$|Y_{pm}(w_k)Y_c(w_k)|^2 = \tag{3.14}$$

$$\frac{A_{ek}^2|Y_{pa}(w_k)Y_c(w_k)|^2 + \Phi_{nn}(w_k)\delta w_k|F_{xm}(w_k)|^2}{A_{ek}^2 + \Phi_{nn}(w_k)\delta w_k|F_{xe}(w_k)|^2}$$

Shirley derived:

$$\Phi_{nn}(w_k) = \frac{M_{nn}^2(w_k)}{\delta_{wk}|F_{xm}(w_k)|^2(\Delta t)^2} \tag{3.15}$$

and from eq. 3.13 and 3.15

$$A_{ek}^2 = \frac{|e(w_k)|^2}{(\Delta t)^2} - \frac{M_{nn}^2(w_k)\ \ \delta w_k|F_{xe}(w_k)|^2}{(\Delta t)^2\ \ \delta w_k|F_{xm}(w_k)|^2} \tag{3.16}$$

Applying eq. 3.10 and 3.11 to 3.16,

$$A_{ek}^2 = \frac{|e(w_k)|^2 - M_{nn}^2(w_k)}{(\Delta t)^2} \tag{3.17}$$

Also,

$$\Phi_{nn}(w_k)\delta w_k|F_{xm}(w_k)|^2 = \Phi_{nn}(w_k)\delta w_k|F_{xe}(w_k)|^2 \tag{3.18}$$

$$= \frac{M_{nn}^2(w_k)}{(\Delta t)^2}$$

Substituting in eq. 3.14,

$$|Y_{pm}(w_k)Y_c(w_k)|^2 = \tag{3.19}$$

$$\frac{\dfrac{|Y_{pa}(w_k)Y_c(w_k)|^2}{(\Delta t)^2}[|e(w_k)|^2-M_{nn}^2(w_k)] + \dfrac{M_{nn}^2(w_k)}{(\Delta t)^2}}{\dfrac{|e(w_k)|^2 - M_{nn}^2(w_k)}{(\Delta t)^2} + \dfrac{M_{nn}^2(w_k)}{(\Delta t)^2}}$$

$$= \frac{|Y_{pa}(w_k)Y_c(w_k)|^2 \ [|e(w_k)|^2-M_{nn}^2(w_k)] + M_{nn}^2(w_k)}{|e(w_k)|^2}$$

and solving for $|Y_{pa}(w_k)|^2$ gives

$$|Y_{pa}(w_k)|^2 = \frac{|Y_{pm}(w_k)Y_c(w_k)|^2|e(w_k)|^2-M_{nn}^2(w_k)}{|Y_c(w_k)|^2[|e(w_k)|^2-M_{nn}^2(w_k)]} \tag{3.20}$$

Equation 3.20 gives the human operator describing function amplitude ratio corrected for the remnant.

3.4 Statistical Significance Tests

The data were analyzed on an individual subject basis and then averaged over all subjects. It was desired to compare two groups of runs such as ROLL FHU and YAW FHD. Means M_1 and M_2 were computed from each group. Since there were at most twenty samples in each group, the t technique[17] was appropriate, with $t = Dm/s_{Dm}$ where $Dm = M_1 - M_2$ and s_{Dm} was the best estimate of the standard error of the difference:

$$s_{Dm} = \sqrt{\frac{s^2}{N_1{}^2} + \frac{s^2}{N_2{}^2}}$$

where

$$s^2 = \frac{\sum_{i=1}^{N_1}(x_i - M_1)^2 + \sum_{i=1}^{N_2}(x_i - M_2)^2}{N_1 + N_2 - 2}$$

so

$$t = \frac{Dm}{s_{Dm}} = \frac{M_1 - M_2}{\sqrt{\frac{s^2}{N_1^{\ 2}} + \frac{s^2}{N_2^{\ 2}}}}$$

Comparison of computed values of t to tabulated values, for the appropriate degrees of freedom and desired level of significance, constituted the test for significance of the difference between two means, M_1 and M_2. The number of degrees of freedom was $N_1 + N_2 - 2$, and $P < .05$ was chosen for significance level. This implies that there is less than a 5% chance that the two means were really part of the same distribution if t computed was greater than t tabulated. It was appropriate to use a one-tailed test when trying to show one mean was greater (or less) than another. To show equality of two means, a two-tailed test was necessary.

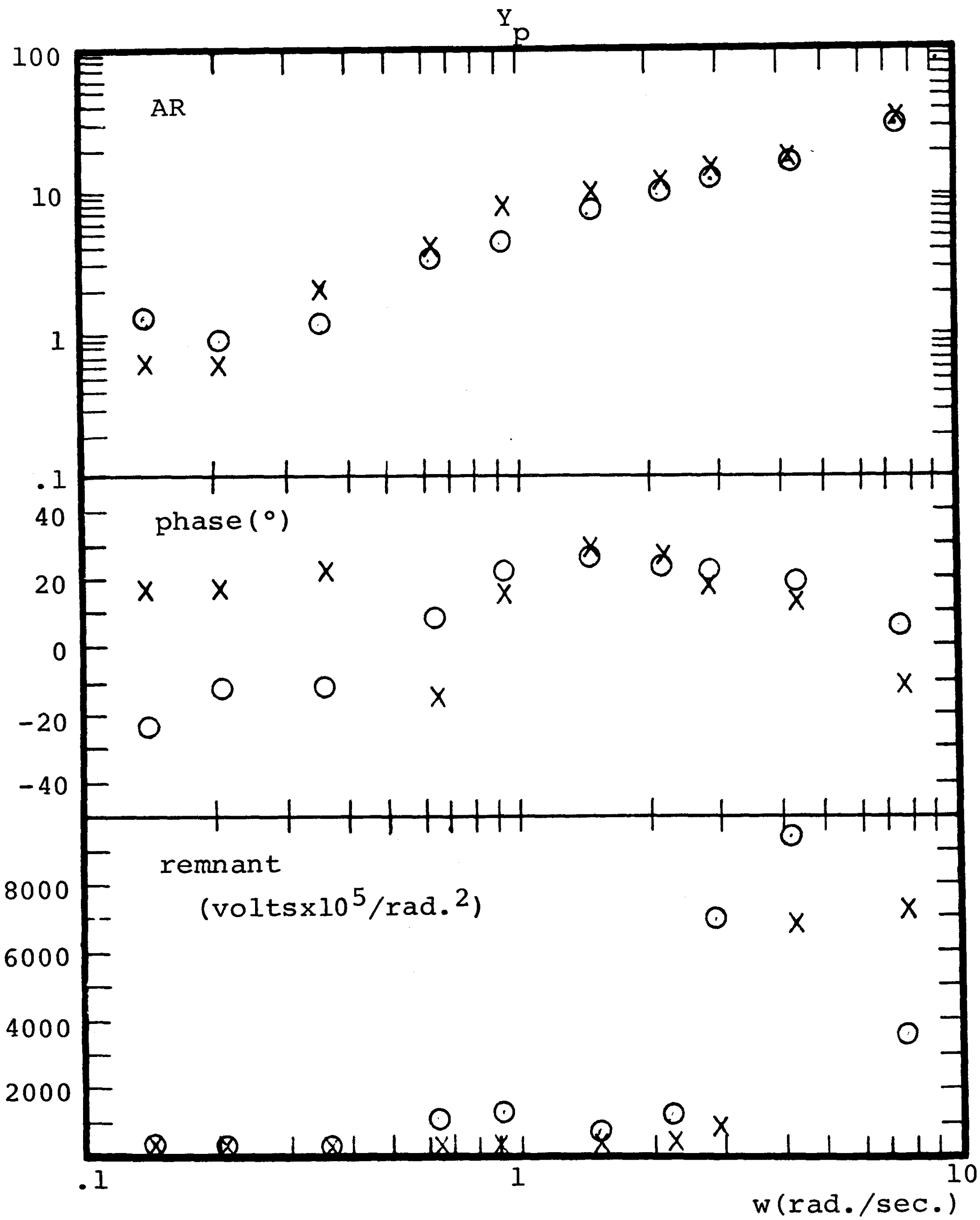
3.5 Validation of the Experimental System

The experimental measurement system was validated by Shirley, who took measurements on known filters and obtained close agreement of theoretical and experimental values. Measurements were taken during these experiments on a known filter (1/(s + 1)), and all data points fell within two percent of theoretical values.

Intersubject variability is discussed at length in Chapter IV of this thesis, in which the data are examined both as grand averages over all subjects and as individual subject results. Run-to-run variability is indicated by standard deviations listed with the data in Appendix A.

Comparison of the composite data obtained for ROLL FHU with data obtained by Shirley for the most nearly comparable system, is shown in Fig. 3.3. An explanation of the figure appears in section 4.1. It is seen in Fig. 3.3 that AR (amplitude ratio) data agree very well. Phase agreement is good at middle frequencies. Shirley's data show more phase lead at high frequencies and more lag at low frequencies. The reasons for this are not clear.

The rISE values obtained in this experiment are consistently lower than those obtained by Shirley. Expressing the ISE in terms of integral square rotation (ISR, in degrees squared) and comparing Shirley's data to the data presented in this thesis reveals that the motion was limited by the human operator to approximately the same integrated value for both cases. Values of ISR for both sets of data are included in the comparison, Fig. 3.3.



x Composite: ROLL FHU, ISR = 8 degrees squared

o Shirley: Motion and Visual, ISR = 9 degrees squared

Figure 3.3
Comparison of experimental results with
Shirley's results

CHAPTER IV

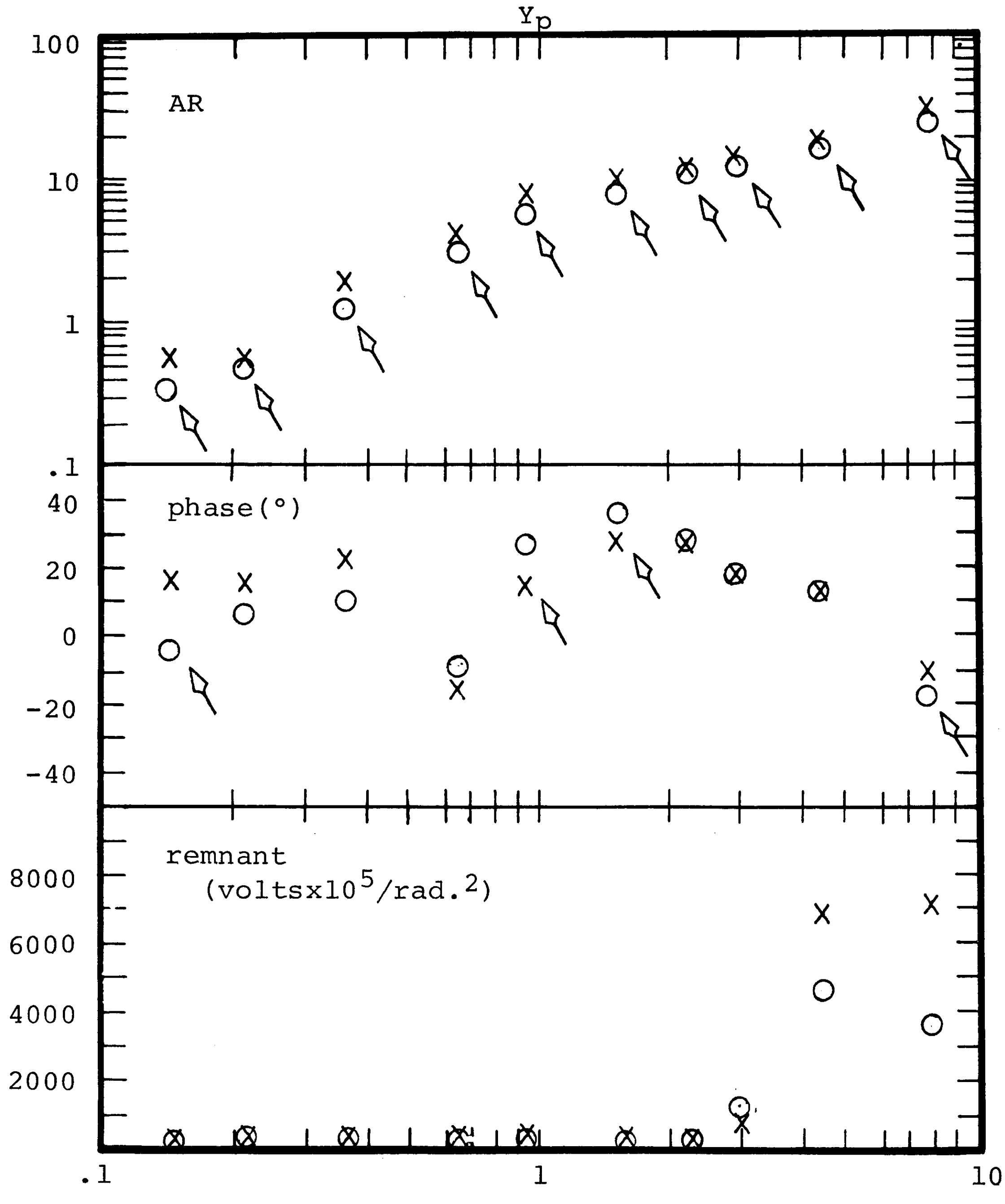
THE EXPERIMENTAL RESULTS

4.1 Presentation of the Data

The data are presented in section 4.2 and in Appendices A and B. Figures 4.1 - 4.12 display $Y_p(jw)$, the human operator's describing function, and the remnant. $Y_p(jw)$ consists of the magnitude (AR for amplitude ratio) and phase of the human operator's output relative to his input. AR is shown in the top section and phase in the middle section of each graph. The AR scale is logarithmic and the phase scale linear in degrees. The remnant is that part of the human operator's output not correlated with his input (see section 3.3), and it is presented as a power spectral density on a linear scale in the bottom section of each graph. The horizontal scale for AR, phase, and remnant is w, in radians per second, plotted on a log scale. The data points are presented at the ten frequencies of the input (section 3.1) between .1 and 10 rad/sec. Arrows at the data points for AR and phase indicate that differences between two results at a given frequency are statistically significant (at the .05 level or more). The "mean rISE" is the mean of rISE scores for runs averaged on a particular graph. All the data are presented in tabular form in Appendix A, including standard deviations. Composite graphs represent averages over all four subjects, five runs each for each situation. Individual graphs are labeled by subject and represent averages over five runs for each situation. Tables 4.1 and 4.2 summarize the composite data. Table 4.1gives the AR for YAW FHU at each frequency and then gives the percentage variation at respective frequencies of the AR for YAW FHD, ROLL FHD, and ROLL FHU. Table 4.2 gives the phase for YAW FHU at each frequency, and variations from this phase at respective frequencies of phases for YAW FHD, ROLL FHD, and ROLL FHU. These tables attempt to show the variations in AR and phase, taking YAW FHU as an arbitrarily chosen standard.

4.2 The Data

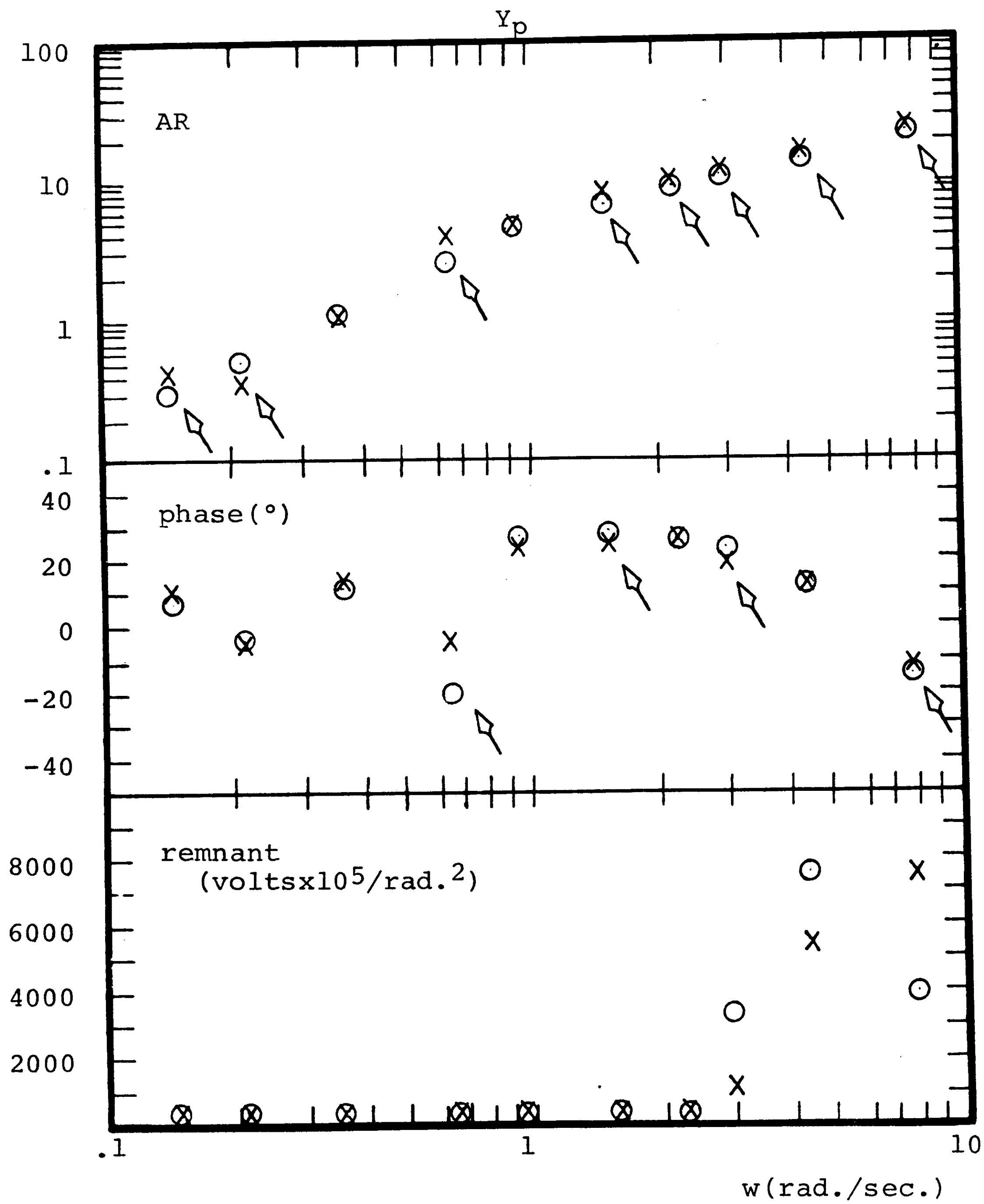
Figures 4.1-4.12 and tables 4.1 and 4.2.



Composite: ROLL FHU and YAW FHD

X ROLL FHU, mean rISE=.16
O YAW FHD, mean rISE=.26
Statistically significant difference (P < .05)

Figure 4.1



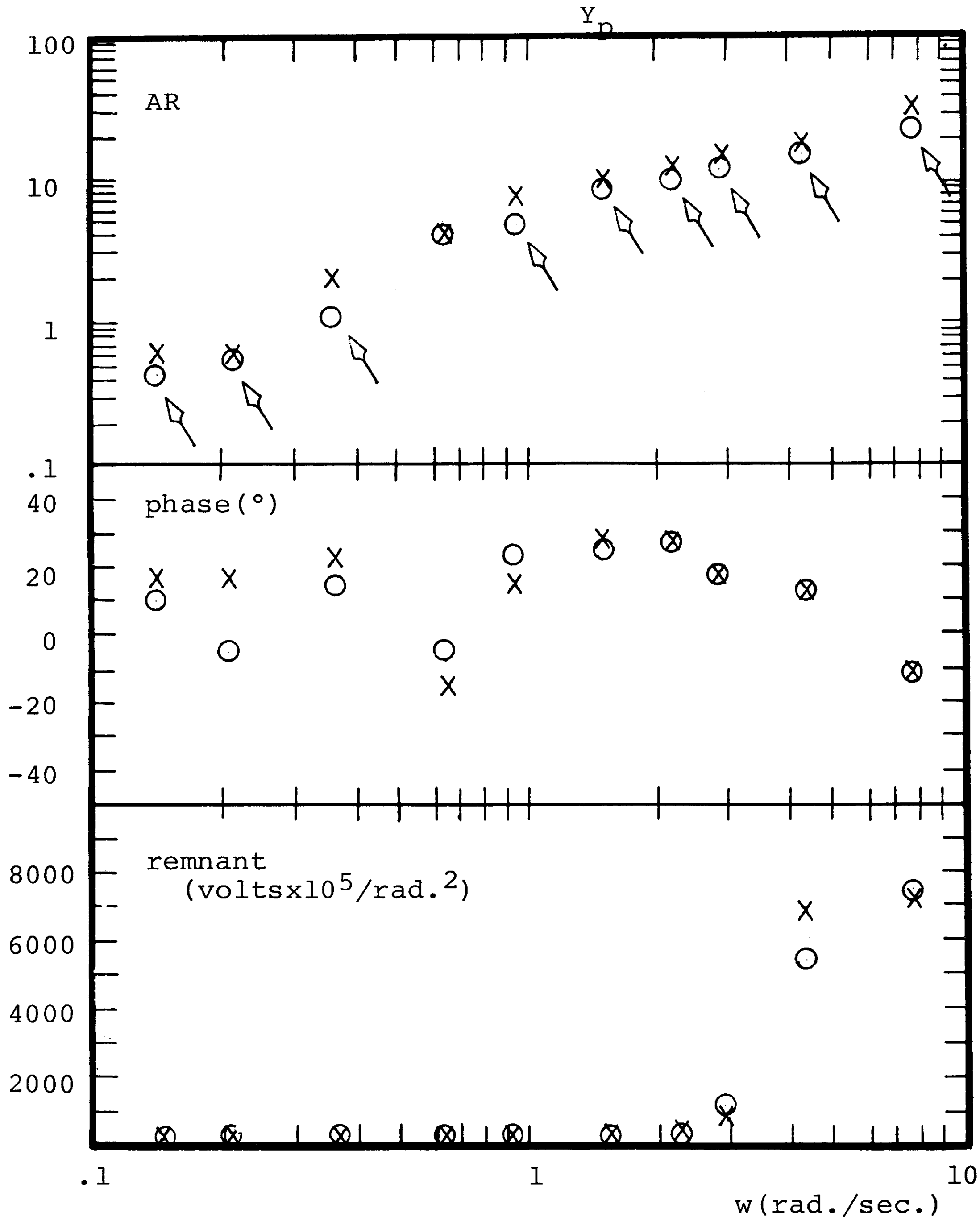
Composite: ROLL FHD and YAW FHU

X ROLL FHD, mean rISE=.30

O YAW FHU, mean rISE=.29

Statistically significant difference (P < .05)

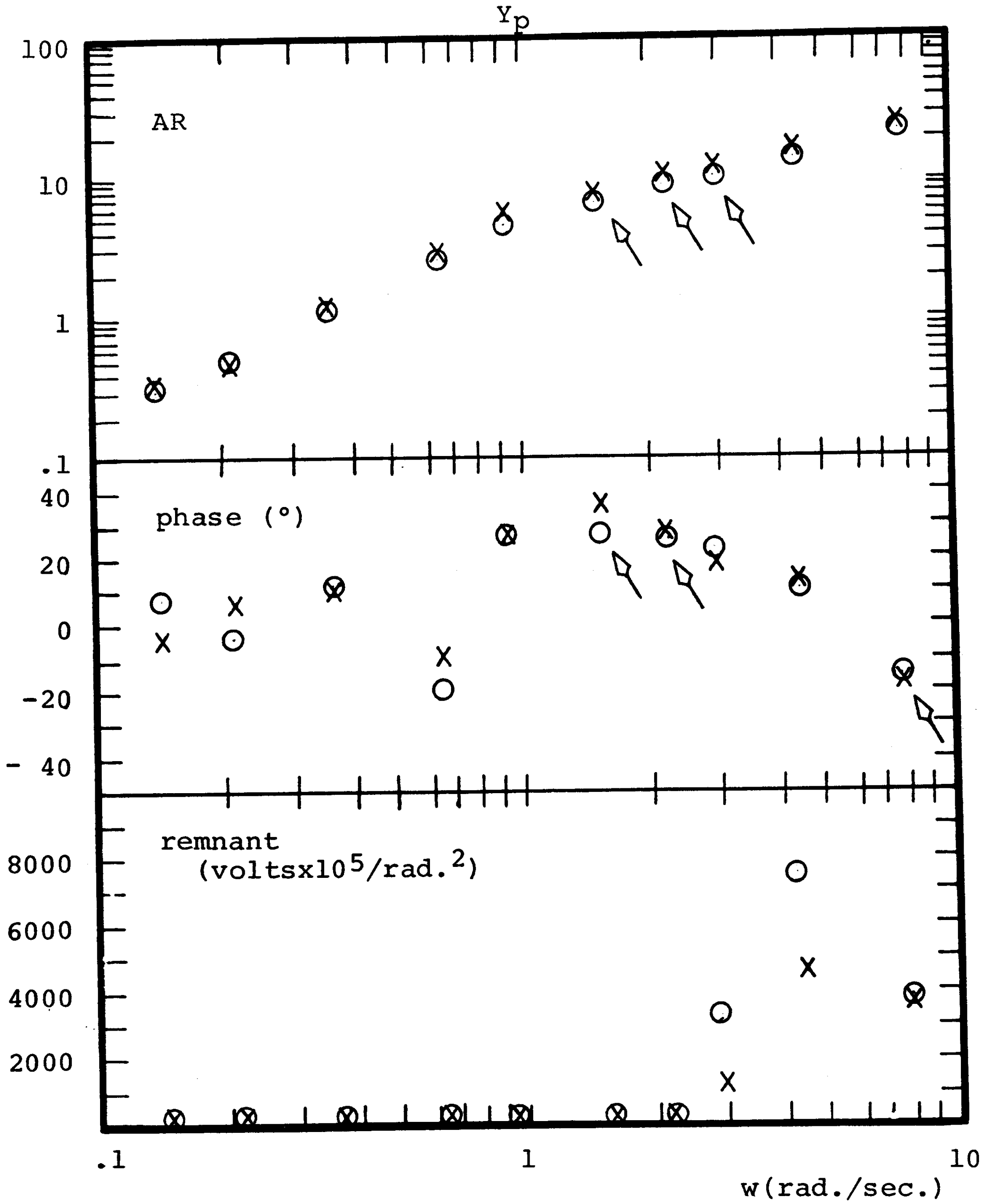
Figure 4.2



Composite: ROLL FHU and ROLL FHD

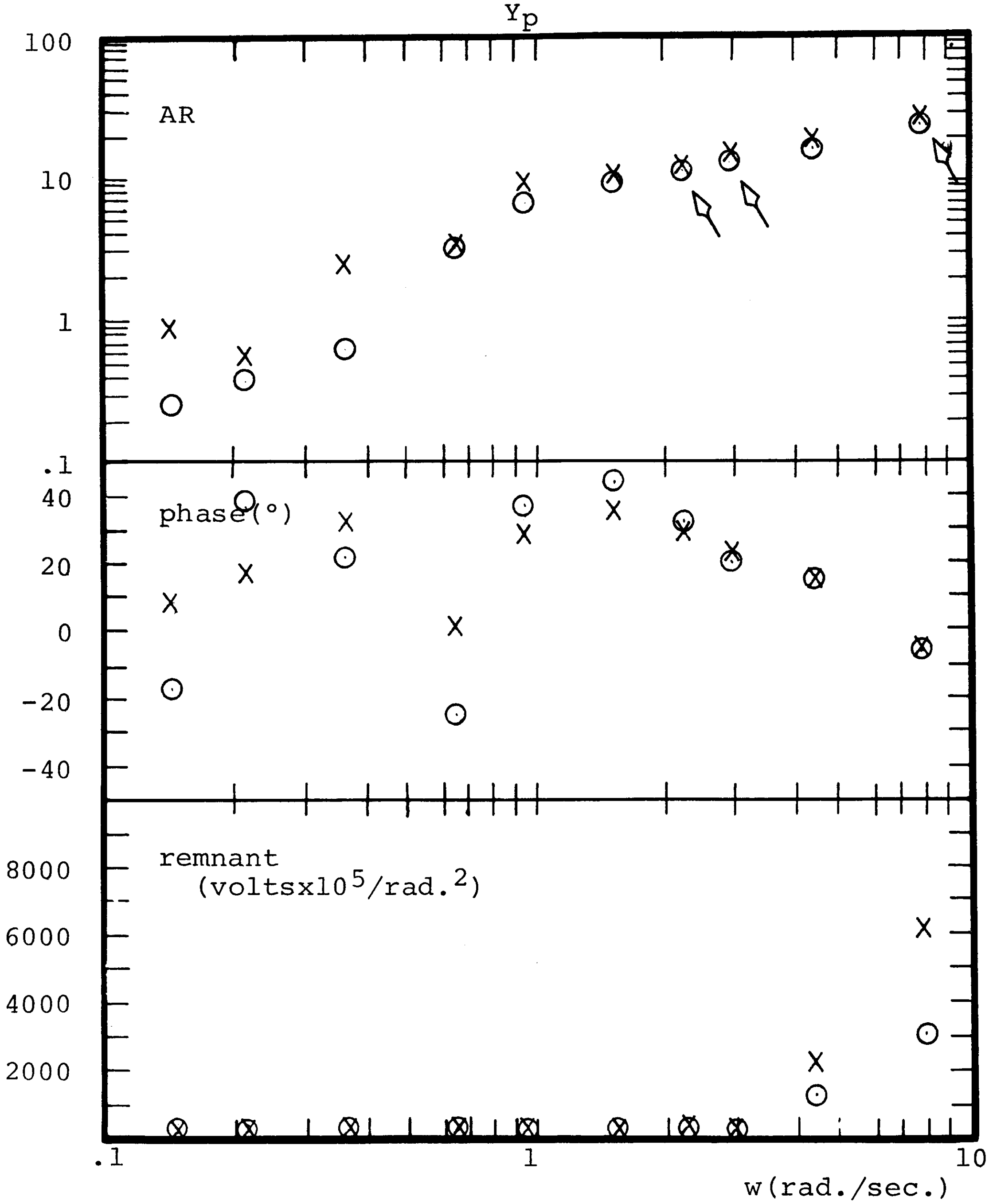
X ROLL FHU, mean rISE=.16
O ROLL FHD, mean rISE=.30
Statistically significant difference ($P < .05$)

Figure 4.3



Composite: YAW FHD and YAW FHU
X YAW FHD, mean rISE=.26
O YAW FHU, mean rISE=.29
Statistically significant difference
(P < .05)

Figure 4.4



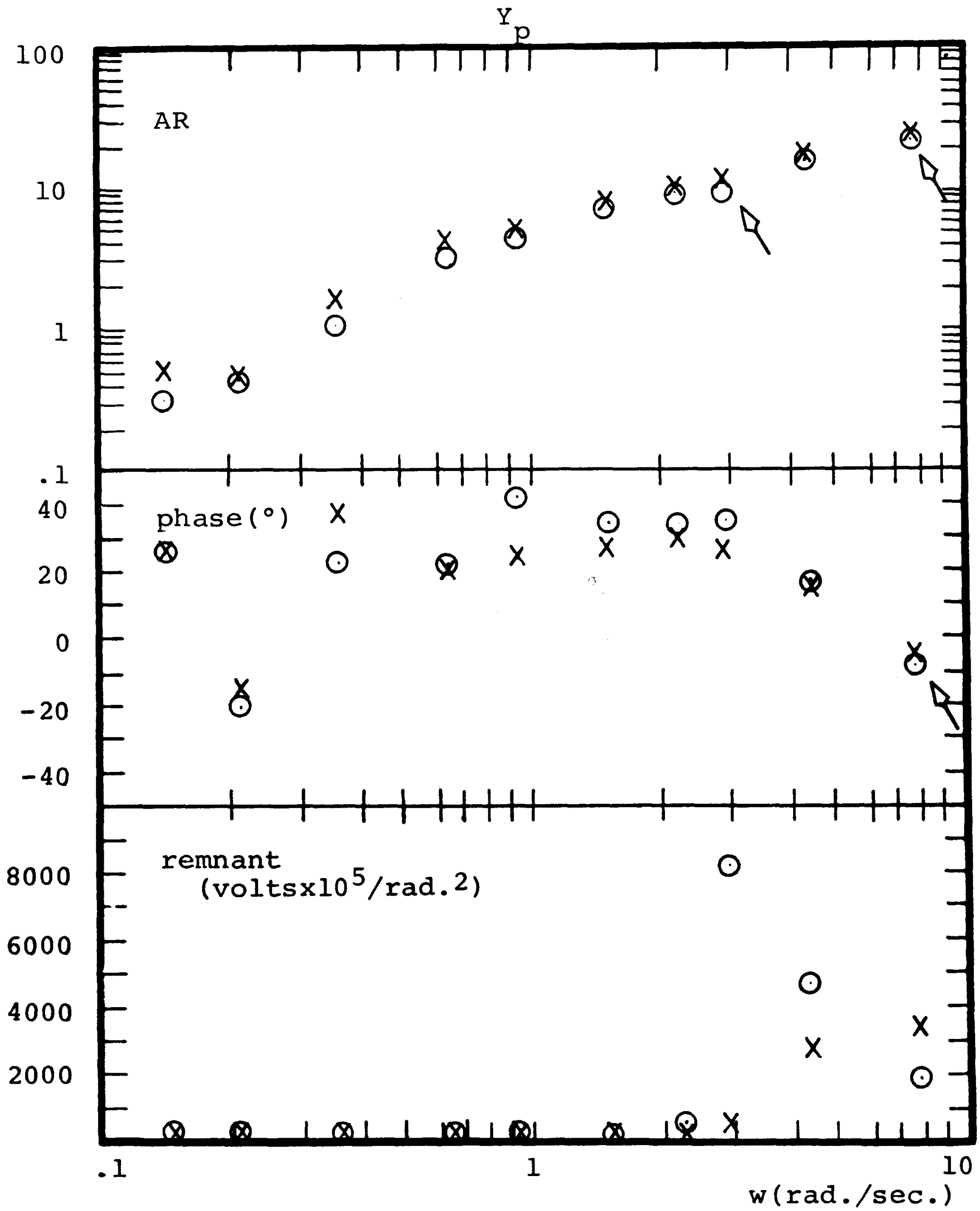
SU: ROLL FHU and YAW FHD

X ROLL FHU, mean rISE=.06

O YAW FHD, mean rISE=.15

Statistically significant difference (P < .05)

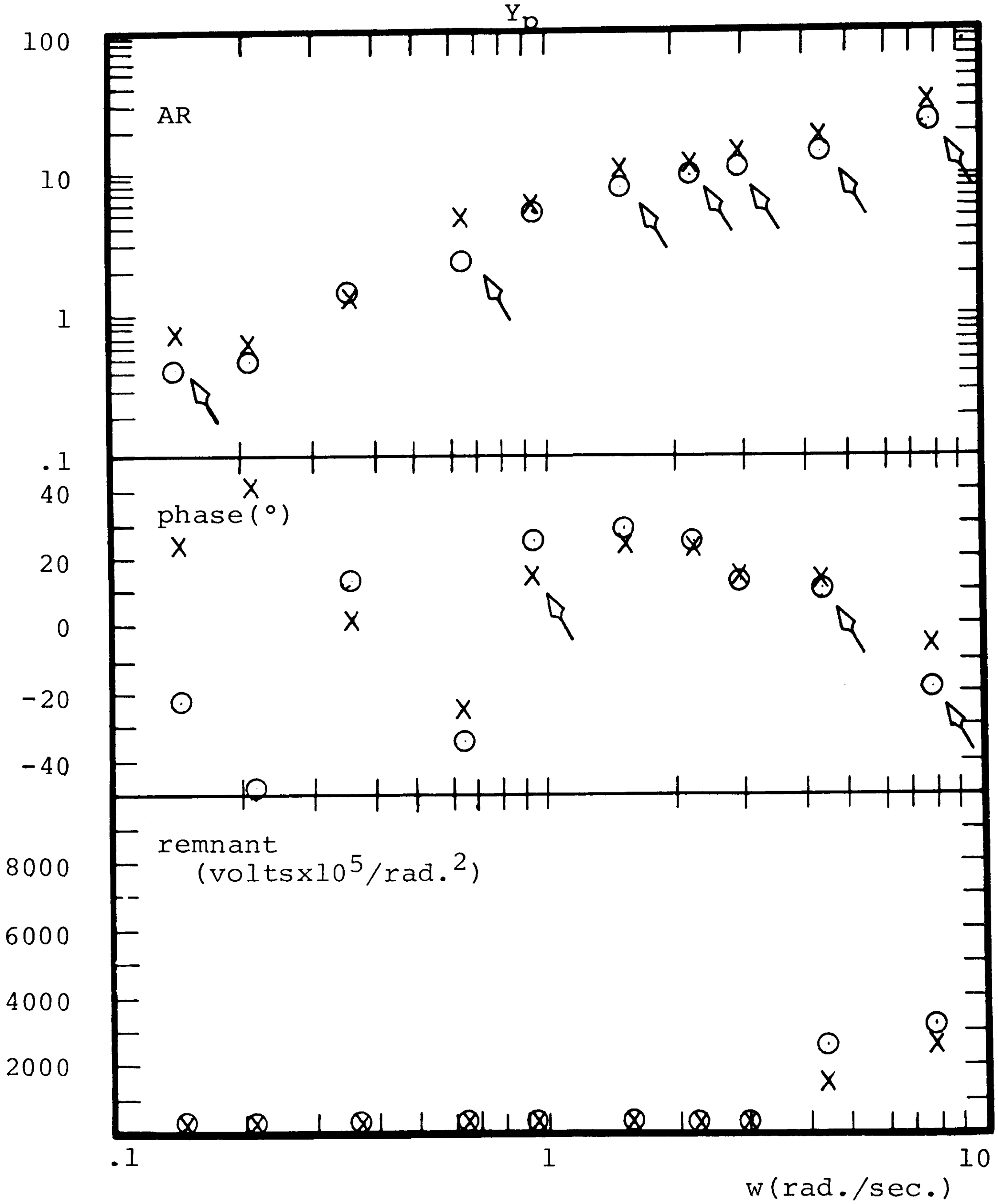
Figure 4.5



SU: ROLL FHD and YAW FHU

X ROLL FHD, mean rISE=.15
O YAW FHU, mean rISE=.23
Statistically significant difference (P < .05)

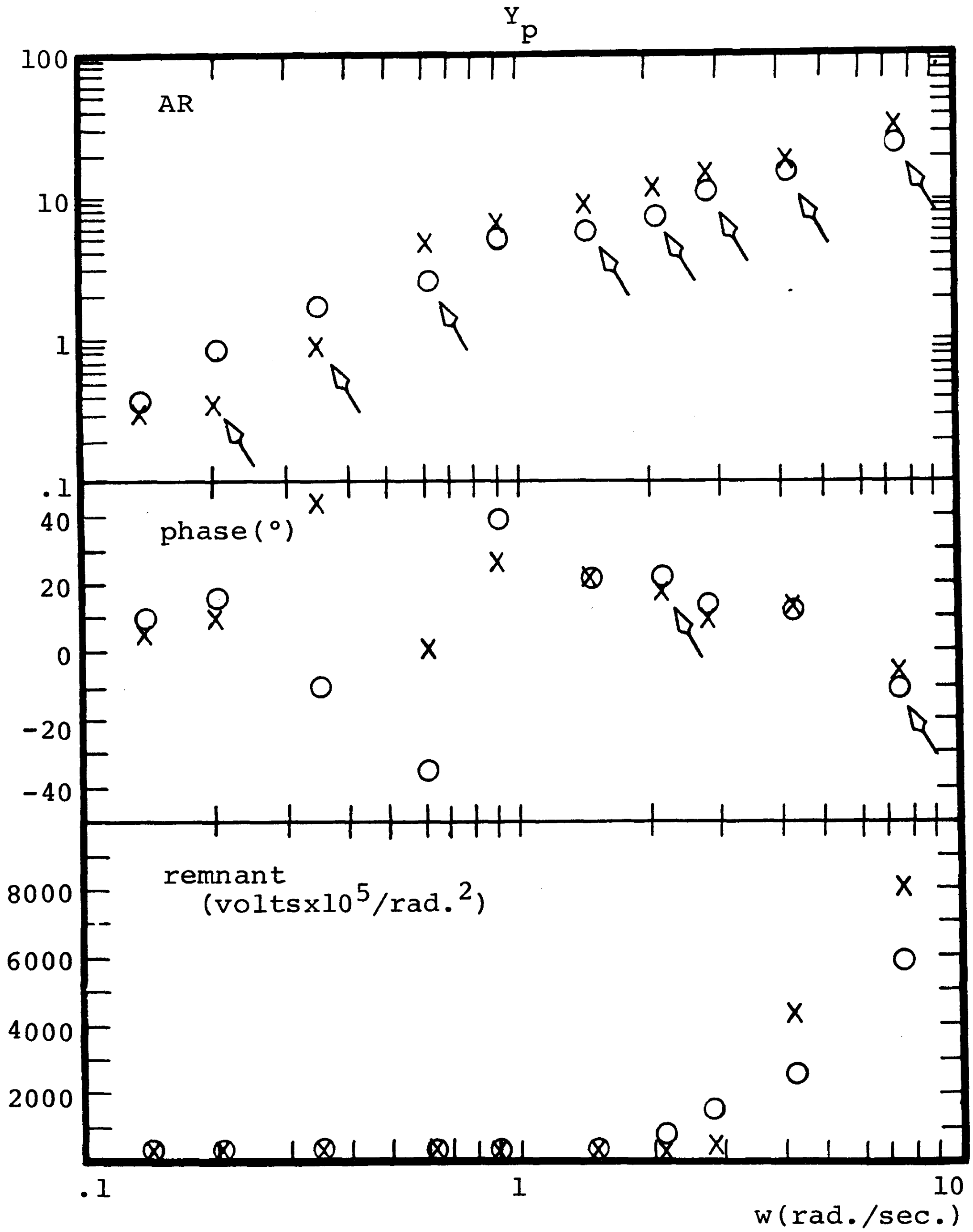
Figure 4.6



TI: ROLL FHU and YAW FHD

X ROLL FHU, mean rISE=.11
O YAW FHD, mean rISE=.22
Statistically significant difference ($P < .05$)

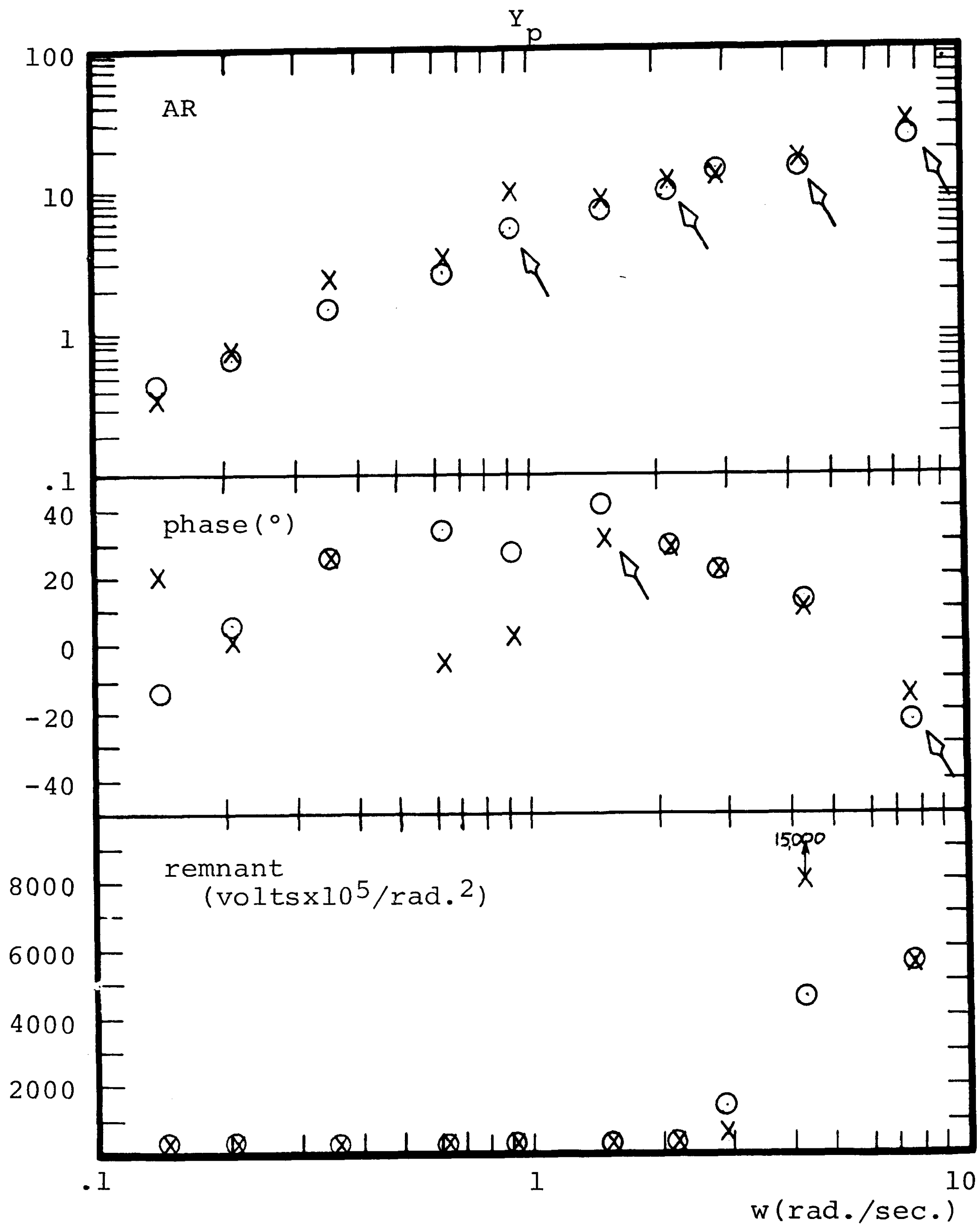
Figure 4.7



TI: ROLL FHD and YAW FHU

X ROLL FHD, mean rISE=.20
O YAW FHU, mean rISE=.25
Statistically significant difference ($P < .05$)

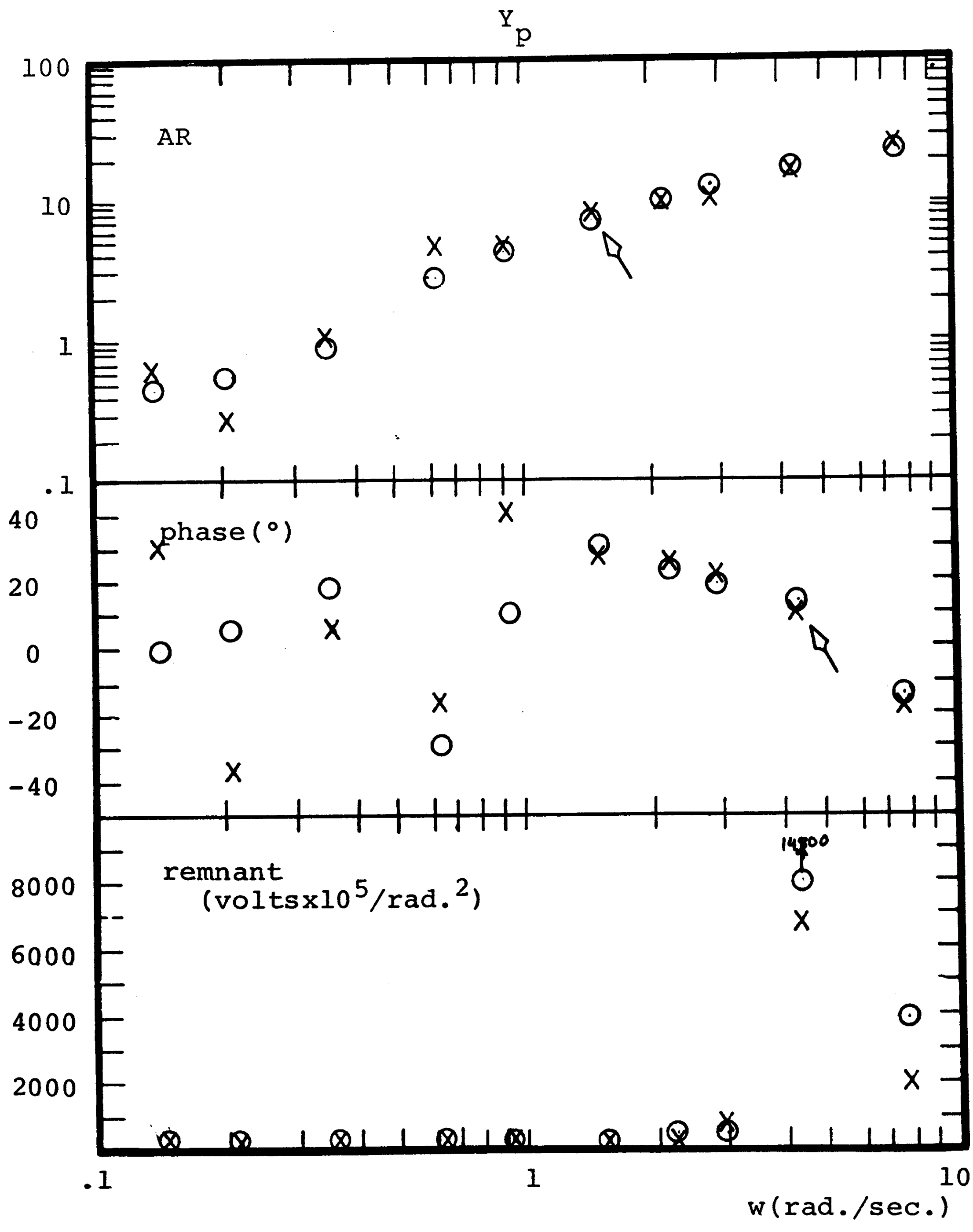
Figure 4.8



JG: ROLL FHU and YAW FHD

X ROLL FHU, mean rISE=.14
O YAW FHD, mean rISE=.19
Statistically significant difference ($P < .05$)

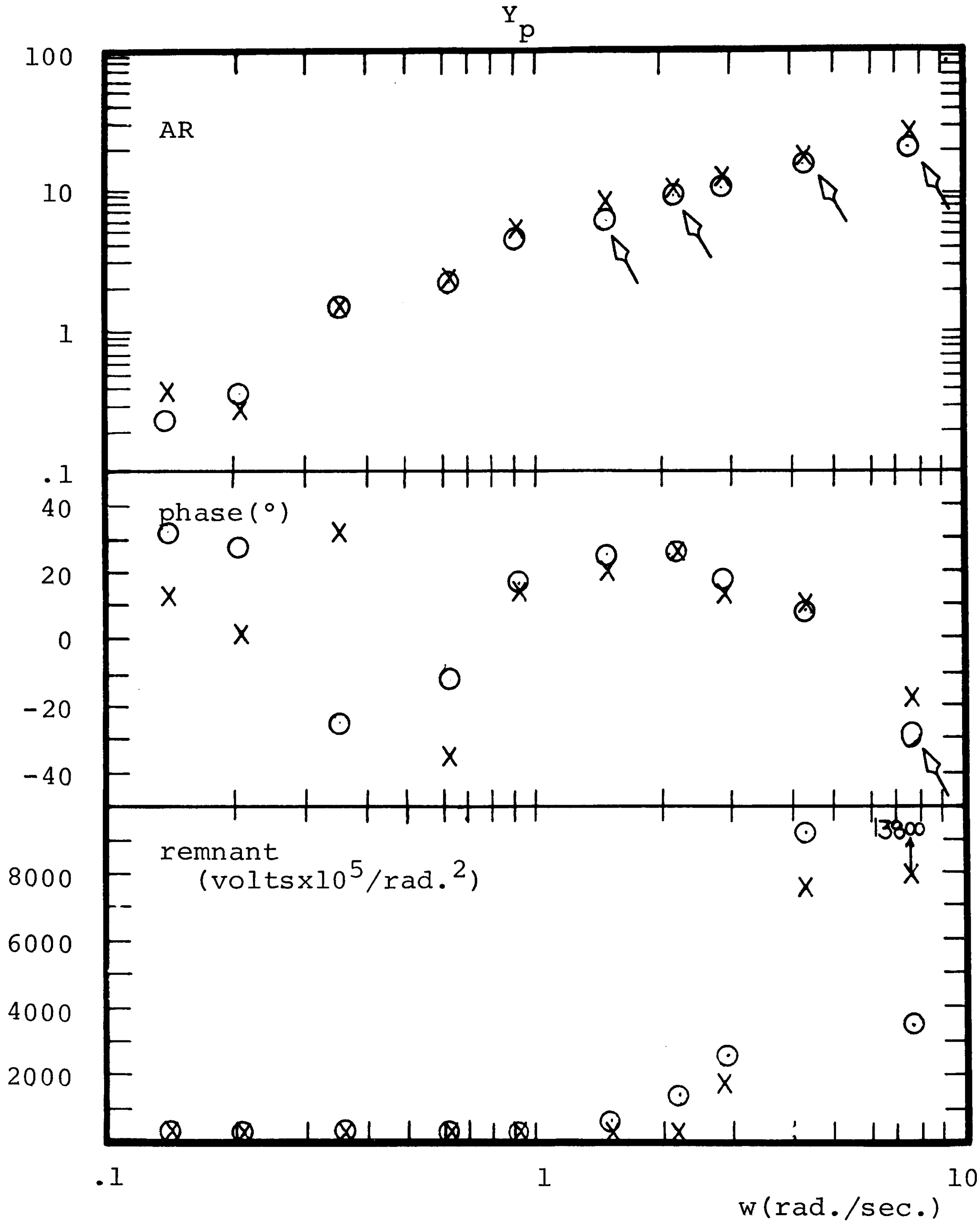
Figure 4.9



JG: ROLL FHD and YAW FHU

X ROLL FHD, mean rISE=.25
O YAW FHU, mean rISE=.18
Statistically significant difference (P < .05)

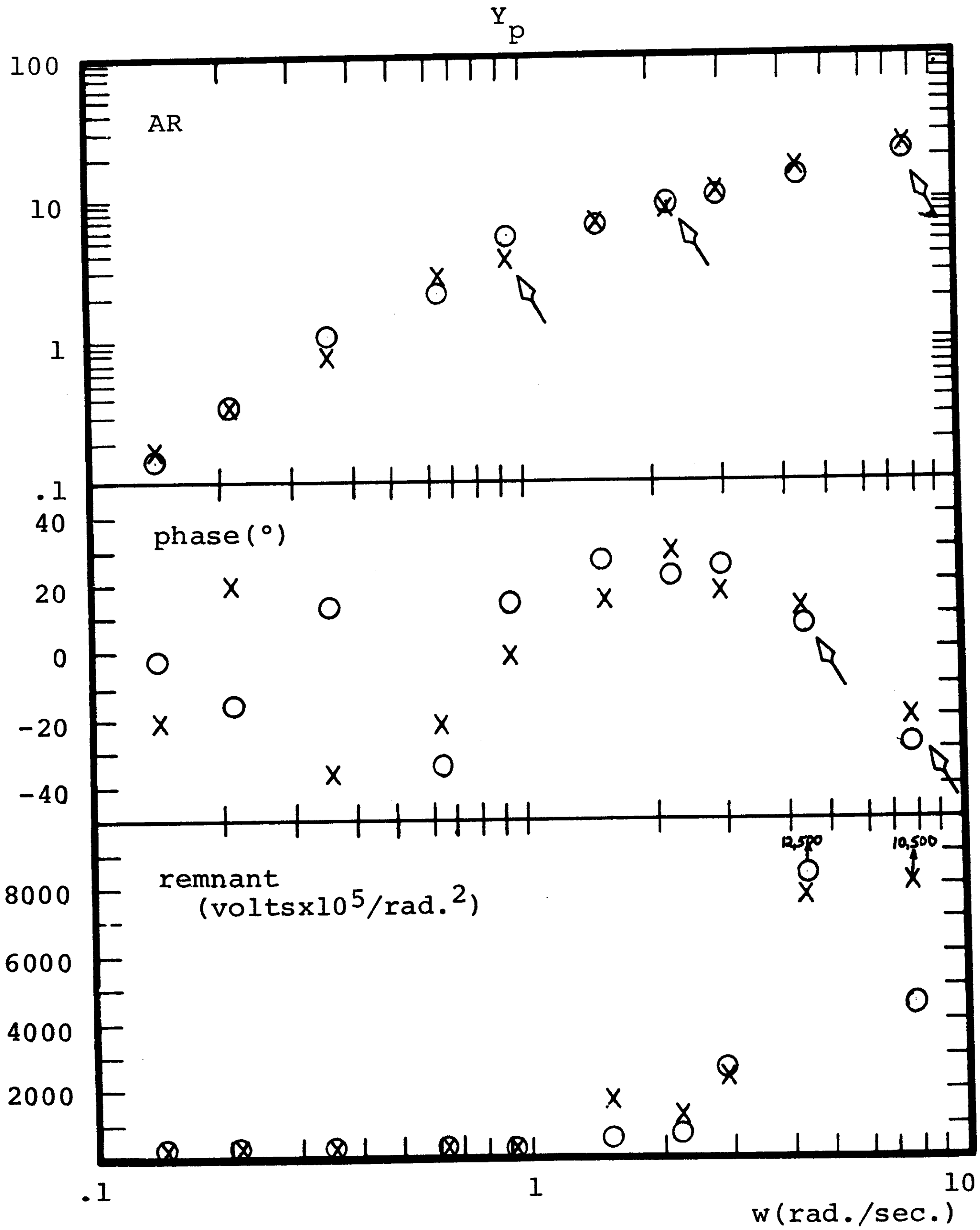
Figure 4.10



BP: ROLL FHU and YAW FHD

X ROLL FHU, mean rISE=.31
O YAW FHD, mean rISE=.48
Statistically significant difference ($P < .05$)

Figure 4.11



BP: ROLL FHD and YAW FHU

X ROLL FHD, mean rISE=.59
O YAW FHU, mean rISE=.48
Statistically significant difference (P < .05)

Figure 4.12

Table 4.1
Composite Results
AR-Comparison

Frequency (rad/sec)	AR for YAW FHU	% Change in AR-YAW FHD	% Change in AR-ROLL FHD	% Change in AR-ROLL FHU
.14	.31	+10	+39	+90
.21	.55	-11	-33	+6
.35	1.2	+8	-8	+60
.63	2.7	+10	+56	+48
.91	5.1	+12	+2	+53
1.5	7.0	+12	+16	+40
2.2	9.2	+12	+12	+32
2.9	11.5	+11	+7	+26
4.3	16.6	+3	+7	+14
7.7	23.2	+2	+10	+30

Table 4.2
Composite Results
Phase-Comparison

Frequency (rad/sec)	Phase for YAW FHU	Change(°) in Phase-YAW FHD	Change(°) in Phase-ROLL FHD	Change(°) in Phase-ROLL FHU
.14	+8	-13	+3	+8
.21	-4	+10	-1	+19
.35	+11	-1	+2	+12
.63	-20	+11	+16	+4
.91	+27	0	-4	-12
1.5	+29	+6	-5	-1
2.2	+25	+3	+1	+2
2.9	+23	-5	-4	-5
4.3	+12	0	0	0
7.7	-15	-4	+3	+4

4.3 General Results

Comparison of the composite results for ROLL FHU and YAW FHD (Fig. 4.1) reveals that AR in ROLL FHU is significantly greater than AR in YAW FHD. Also phase lead at the highest frequency is significantly greater in ROLL FHU than in YAW FHD. Phase lead at the two middle frequencies is significantly less in ROLL FHU compared to YAW FHD. The same ROLL-YAW results hold in comparison of ROLL FHD and YAW FHU (Fig. 4.2), although the differences are not as great in the latter case.

Each individual consistently produced the type of results observed in the composite. This is especially noted for the case ROLL FHU versus YAW FHD, where ROLL AR is significantly greater than YAW AR at an average of four frequencies per subject. There are few significant phase differences because of the spread in phase data. In all the data the AR measurements show much less "scatter" than the phase measurements. That this is characteristic is noted by McRuer et al.[16] It makes generalizations about changes in the human operator lead or lag difficult to demonstrate. At low frequencies in particular, the standard deviations are very large, making statistical significance rare.

The few phase differences that are significant are consistent, with ROLL FHU phase lead greater than YAW FHD lead at high frequencies and vice versa at middle frequencies. Comparison of ROLL FHD and YAW FHU is somewhat equivocal for BP and JG (Figs. 4.9 - 4.12), although TI and SU (Figs. 4.5 - 4.8) match the composite results very well. These are individual differences which will be discussed subsequently. It may be observed from Fig. 4.3 that ROLL FHD AR are consistently less than ROLL FHU AR, while the phases are nearly the same. Thus, althoug the results show that overall ROLL FHD AR are significantly greater than YAW FHU AR (Fig. 4.2), the differences are smaller than encountered in comparison of ROLL FHU and YAW FHD (Fig. 4.1). The phase differences are equally significant in each case, as shown by comparison of both individual results and composite results. It is seen that the human operator is able to maintain maximum gain in ROLL FHU, somewhat less gain in ROLL FHD, and significantly less gain in yaw, with YAW FHD slightly superior to YAW FHU (Fig. 4.4). Phase lead in ROLL FHU is virtually identical to lead in ROLL FHD (Fig. 4.3) and at high frequencies is significantly greater than phase lead in YAW FHU or YAW FHD (Fig. 4.4). At middle frequencies the situation is reversed. Comparison of phase lead for YAW FHD versus YAW FHU shows very little difference, but YAW FHU allows slightly higher lead at high frequencies and less lead at mid-frequencies.

4.4 Physiological Explanations of the Results

The experiments were designed so that effects of otolith stimulation on motion sensation could be observed. As discussed in section 2.1, Roll FHU approximately duplicates YAW FHD except for otolith stimulation in roll. If postural and tactile effects could be neglected, the results cited above show that otolith stimulation obtained in roll enables the human operator to increase his gain and phase lead at high frequencies. This conclusion is further substantiated by the results of ROLL FHD vs. YAW FHU, in which the awkward postural variable is functioning in roll rather than yaw.

Comparison of ROLL FHU with ROLL FHD (Fig. 4.3) shows ROLL FHU AR significantly greater at all but one frequency than ROLL FHD AR. There is very little significant phase difference. It is clear, however, that the human operator feels that his control is more positive in ROLL FHU than in ROLL FHD, and he can therefore consistently apply more gain.

There are several possible explanations for this difference.* First, in each case a different set of semicircular canals is being utilized. In ROLL FHU two sets of vertical canals are primarily involved. In ROLL FHD the horizontal canals are dominant. Some differences in individual semicircular canal sensitivity and threshold may account for differences in the human operator describing function in ROLL FHU and ROLL FHD. A check on this possibility is provided by data obtained for YAW FHU and YAW FHD. Comparison of the composite data shows no clear-cut difference in response between YAW FHU and YAW FHD. In this regard it must be remembered that

* The distance from the roll axis of the otoliths was the same in ROLL FHD as in ROLL FHU (two feet).

two subjects, SU and BP, were unable to place their heads on the yaw axis in the FHD position. At high frequencies in YAW FHD they would thus be expected to receive some otolith stimulation. The root mean square tangential acceleration at the otoliths in YAW FHD was approximately 0.017 g. Two other subjects, TI and JG, were able to locate their heads in the FHD position on the yaw axis. TI has virtually identical results in YAW FHD and YAW FHU. JG also has very similar results for the two cases, except at lower frequencies where YAW FHD has slightly (not significantly) greater AR than YAW FHU. These results indicate little if any difference in canal sensation.

The possibility exists that possible superiority of the vertical canals is masked by problems associated with the somewhat awkward FHD posture. While tolerable for at least run-length periods, the FHD posture was somewhat uncomfortable. That comfort and performance are related is well known. The mechanism involved may have been the arm-hand-motor activity. FHU posture seemed to provide a more stationary platform for the right arm and thus give more posture control. In addition, the uncomfortable posture may have distracted the subjects' attention from the tracking task somewhat. There is really no way to settle this question without modification of the experimental apparatus to accommodate a supine subject with his head on the rotation axis.

In summary, it seems likely that two factors work to decrease performance in ROLL FHD compared to ROLL FHU. There are possibly differences in dynamic sensing capabilities of the horizontal and vertical canals, and awkward posture may tend to lower performance in the FHD position.

Because the two subjects with heads on the yaw axis in YAW FHD obtained the same results in YAW FHD and YAW FHU, one would expect an observable difference between the two cases for the subjects who could not place their heads on the yaw axis. This is due to otolith stimulation arising from tangential accelerations. This stimulus could supply switching information about the lateral acceleration. Otolith information could be interpreted as a continuous measure of lateral acceleration (magnitude and direction), which the human operator would minimize. In fact, significant differences in the data for SU's runs in YAW FHD and YAW FHU (Figs. 4.5 and 4.6) do appear. It is seen that SU shows consistently (often significant) higher AR in YAW FHD than in YAW FHU. However, BP produced inconclusive results. A comparison of her results for YAW FHD and YAW FHU (Figs. 4.11 and 4.12) reveals no clear-cut tendency.

The remnant at each frequency was calculated as explained in section 3.3. McRuer et al[16] and others have investigated the meaning of the remnant. They conclude that neither bang-bang control behavior nor non-linear transfer characteristics of the human operator are dominant remnant sources. They indicate the major source of remnant is time-varying behavior during runs, specifically, changing phase shift. This accounts to some extent for the spread in the phase data. Comparison of remnant values among subjects indicates that SU and TI tended to be the steadiest operators and BP the least steady. ROLL FHD produced the most time-varying behavior and YAW FHD the least, although differences were not large.

4.5 Subject Discussion

Further insight into the meaning of the data may be had by examining the results for each subject in light of observations about his performance. All four subjects were highly experienced in the same control task in roll with head unfixed. In training, their performance in yaw rapidly equaled or nearly equaled their roll performance as determined by rISE scores. However, individuals reached quite different plateaus of performance.

The subject's performance during runs was monitored at the computer by a dual-beam oscilloscope on which were displayed the error input to the subject and his control stick output. The error was a smooth continuous signal as opposed to the very rough discontinuous control stick output. Most of the comments that follow are based on observations of the monitor.

4.5.1 SU

SU was capable of extremely low rISE scores and as an index, averaged .06 (rISE) for ROLL FHU. His tracking behavior was consistently the most aggressive and his error tolerance was lower than any of the other subjects'. This is also revealed in his describing function. Figures 4.5 and 4.6 show his phase lead at high frequencies to be very nearly the same for each set of runs, and greater than any of the other subjects'. However, he varied his AR to fit each situation. It is somewhat puzzling that he applied less gain than other subjects even though he was better equipped to do so by virtue of his increased phase lead. In his case, however, lead remains constant, and gain varies with varying degrees of otolith stimulation.

The fact that SU could not get his head on the yaw axis in YAW FHD accounts for his higher gain in that position, if indeed the hypothesis presented in section 4.4 is correct. Also, the AR in ROLL FHD is less than in ROLL FHU because of the effects discussed in section 4.4. While few of the differences in AR and phase for SU's results are significant, they are virtually all in the same direction as the composite results which are statistically significant.

4.5.2 TI

TI is an experienced pilot with a commercial pilot's license. His control mode was much like SU's but differed in that it was smoother. His error tolerance was somewhat higher, his average rISE in ROLL FHU being .11. His results were by far the most consistent. As readily seen from Figs. 4.7 and 4.8, the differences in AR between ROLL FHU and YAW FHD, and between ROLL FHD and YAW FHU are nearly all statistically significant. He was very much in control of his physical capabilities and could respond readily to a requested mode of tracking. For example, a request to disregard the meter display except for an occasional glance for reference information elicited exactly the desired behavior. In this control task he had to abandon a normal flight criterion, namely smooth control for passenger comfort, to minimize his ISE. He succeeded very well at this, but vestiges of airplane handling behavior remained and served to differentiate his slightly smoother control from SU's control. He did not develop as much lead as SU. This may have been due to his control mode or to physical limitation.

The large phase lag at the highest frequency in YAW FHD compared to YAW FHU can only be explained by the awkward position of FHD. This is the only explanation available because TI had his head on the yaw axis in both cases, and received no time varying otolith stimulation. Also, visual acuity was no problem in yaw. The surprising thing about TI's results is the nearly identical results obtained for both roll sets and both yaw sets. The reason for this is probably his learned ability to utilize otolith information and reject spurious visual effects.

4.5.3 JG

In ROLL FHU JG had an average rISE of .14. His control behavior was definitely less aggressive than SU or TI. When watching the oscilloscope display while TI and SU were running it was never in doubt that they were in full control. JG never lost control, but the display gave cause for some doubt at times. His phase lead at high frequencies was considerably less than either of the two previous subjects, although the addition of otolith stimulation (in roll) did help increase his lead at the highest frequency. JG also had a larger phase lag at the highest frequency in YAW FHD than in YAW FHU, with the same 8 degrees difference as TI. The same explanation is necessary for JG as for TI, since he too was able to locate his head on the yaw axis in the FHD position. Comparison of ROLL FHU and YAW FHD (Fig. 4.9) reveals larger AR in roll and more phase lead at high frequencies in roll. A ROLL FHD and YAW FHU comparison (Fig. 4.10) reveals one significant AR (in the wrong direction). Thus ROLL FHD and YAW FHU give similar results with large standard deviations. Perhaps the reason JG dropped his gain so much in ROLL FHD was his inability to reject spurious otolith sensation, which ability TI probably acquired through training.

4.5.4 BP

The fourth subject, BP, averaged .31 rISE for ROLL FHU and had some difficulty in maintaining vehicle control even though she had more training than other subjects. Her control activity was very unaggressive appearing on the monitor display, and she responded only to relatively large amplitude error changes. Her response was visibly slow and quite smooth. She did very much better when the visual display was not delayed, confirming a suspicion that she tried to anticipate the error signal. This control mode made inevitable some control reversals, and this made her lose control momentarily several times. Comparison of ROLL FHU and YAW FHD (Fig. 4.11) shows higher AR in ROLL FHU and more lead for roll at high frequencies. The same results are evident in comparison of ROLL FHD with YAW FHU (Fig. 4.12), except that, as usual, differences are not as pronounced or consistent. She also exhibits more phase lag in YAW FHD than in YAW FHU, which again could be attributable to the awkwardness of the FHD position. The extra lag is evident, however, only at the highest frequency and is not even close to being statistically significant. She did not have her head on the yaw axis, and perhaps, as mentioned earlier, otolith stimulation helped to diminish the lag in FHD position. It is clear that her phase lead was by far the least of any of the subjects, as we would expect from observations of her control behavior.

4.6 Fixed vs. Free Head Position

Control experiments were done to determine the effect of having the head fixed versus unfixed, and to see approximately what effect visual cues in roll have. The latter has been thoroughly covered by Shirley, and this was an attempt to tie in with his results. The data are presented in Appendix B.

Figures B.1 - B.4 indicate that the FHU position enabled both TI and SU to improve their yaw results slightly, compared to head free, and SU had better roll results with FHU than head free while TI had the same results in each case. The purpose of the FHU posture was twofold:

1. to locate precisely the position of the head.
2. to eliminate the effect of head motions relative to the body.

The subjects remarked that the FHU position gave them better visual acuity because their eyes were fixed relative to the meter display.

Performance in ROLL FHU and FHD with motion cues only gave substantially the same results as obtained with motion and visual cues. Figure B.5 shows the greatest difference obtained in all control experiments. The phase lead was virtually identical at middle and high frequencies for TI. But, limited to motion cues only, SU managed to increase his lead at the highest frequency in both ROLL FHD and ROLL FHU. Shirley's data shows this phenomenon in several cases for a $1/s^2$ system. Perhaps this represents incomplete rejection of high frequency visual cues by SU when both motion and visual cues were present. These control experiments confirm Shirley's results that visual cues have little effect in roll high frequency response.

4.7 Summary

The results of this chapter indicate that human operator frequency response in a compensatory system is better in ROLL FHU than in YAW FHD, where the same semicircular canals are being stimulated. Frequency response is also better in ROLL FHD than in YAW FHU. Discussion of the experimental system in this and the preceding chapters has shown that the difference can only be accounted for by the presence of otolith stimulation in roll and its absence in yaw.

CHAPTER V

CONCLUSIONS

5.1 Conclusions

It is now well known that motion cues aid human operator response at high frequencies in compensatory tracking tasks. It is clear that most angular accelerations stimulate the otoliths to some degree, but the extent of otolith contribution to motion sensation was unknown. The data presented in Chapter IV indicate that otolith stimulation in angular rotation aids the human operator's frequency response above and beyond semicircular canal stimulation.

Table 5.1 illustrates the effects of roll motion cues and yaw motion cues in compensatory tracking for K/s^2 vehicle dynamics. Part A of the table was taken from Shirley's data and gives percent change in the AR of the human operator's describing function at each of ten frequencies when roll motion cues are added to visual cues. Part B gives the same information when roll motion cues are added to yaw motion cues. Averaged over the frequencies, a 43% increase in AR occurs when roll motion cues are provided as compared to fixed base AR. An average 25% increase in AR occurs with roll motion cues as compared to yaw motion cues. It is concluded that for a K/s^2 system,

Table 5.1

Effects of motion cues on human operator describing functions for a K/s^2 system

Frequency (rad/sec)	% Change in AR at each freq. when roll motion cues are added to visual cues*	% Change in AR at each freq. when roll motion cues are added to yaw motion cues†	Phase Change in deg. at 5 freq. when roll motion cues are added to visual cues*	Phase Change in deg. at 5 freq. when roll motion cues are added to yaw motion cues†
.14	+20	+73		
.21	+60	+19		
.35	+72	+54		
.63	+21	+33		
.91	+85	+37		
1.5	+75	+26	-7	-7
2.2	+35	+18	-14	-1
2.9	+50	+14	-10	0
4.3	+25	+11	+8	0
7.7	-12	-28	+45	+8
	average change: +43%	average change +25%		

* from Shirley (ref. 11), data for $Y_c(s) = \frac{100e^{-.1s}}{s^2}$

† Comparison of ROLL FHU and YAW FHD (this thesis)

yaw motion cues with head near the yaw axis, enable the human operator to increase AR over the frequency range .1 to 8 rad/sec by an average 18%. He can increase his AR another 25% if roll motion cues are provided. Comparison of phase data in part C of Table 5.1 indicates that little difference occurs in phase between yaw and roll except at the highest frequency. However, large differences occur between roll and fixed base. The conclusion is that lead generated by motion cues is generated nearly as well in yaw as in roll.

5.2 Applications

The results presented above provide useful information in understanding the importance of linear and angular motion cues in a moving base simulator. For any simulation the desired motion is usually complex, and the decision that must be made concerns the type of simulator to use. The answer inevitably involves compromise because of the expense of six-degree-of-freedom simulators. Even if such a simulator is available, linear motion cues must be restricted in magnitude because of size limitations. A viable approach to this problem is to determine which motion cues occur in the desired maneuvers and which are too important to neglect in the simulation.

The conclusions of this thesis emphasize the importance of otolith stimulation to obtain maximum human operator performance in vehicle control. In terms of simulators, this recommends the use of linear motion cues in the simulation if they are expected to occur in a rapidly time-varying, large magnitude fashion in a difficult control task.

Most conventional aircraft landings involve roll, pitch, up-down, and front-back motions. Yaw and side-to-side motions are less important. Pitch angle is usually slowly varying because of more or less constant glide angles and limited control surfaces, whereas roll angle often varies quite rapidly. Lateral linear cues are important in V/STOL simulations because of sideslip. Linear motion cues in the direction of travel assume obvious importance in space application. Landing maneuvers on the moon will involve primarily the up-down motion cues. For simulation of such a system the linear motion cues provided would be very important, enabling as much as a 50% increase in gain and large phase lead increases by the human operator. Simulation of this situation would be particularly easily done in a linear acceleration cart. Possible areas of concern for human performance in space should include difficult roll maneuvers. In the absence of a force field such maneuvers become more difficult, and the vehicle might become uncontrollable. Hence training should be done in yaw to insure vehicle controllability in the absence of a force field. An additional reason for yaw training for space roll maneuvers is the possibility that otolith impairment from long-term inactivity might occur.

5.3 Recommendations for Future Research

Much of the speculation of preceding sections could be definitely established or refuted with some experiments suggested below. The first set of experiments should provide subjects with a control task and measure the human operator's describing function ($Y_p(jw)$) in the following situations:

1. supine subjects rotated about a vertical axis through their head.
2. subjects lying on their right or left side, rotated about a vertical axis through their head.

If $Y_p(jw)$ were obtained for these situations in the same manner as it was obtained in this thesis for YAW FHU, strict comparisons of semicircular canal contributions in roll (1), yaw (YAW FHU), and pitch (2) would be obtained. Any differences in orientation of the canals with respect to motion would then have known results, in terms of quantitative increment or decrement of performance.

A second experiment would test otolith sensing capabilities. $Y_p(jw)$ should be measured for subject response to a control task in a linear accelerator for the following situations:

1. subjects accelerated facing forward in normal sitting posture.
2. subjects accelerated facing sideways in normal sitting posture.
3. subjects accelerated facing up in supine position.

These situations would establish otolith contribution to vehicle control in linear translation forward and backward (1), linear translation from side-to-side (2), and linear translation up and down (3). Situation 3 might be better accomplished in a servo-controlled elevator to include the normal vertical one-g bias.

A useful area of research is drift velocity and direction in yaw in the absence of a visual reference. It could be determined if direction of drift and velocity of drift are fixed for an individual. Physiologically this might correspond to cupula offset in the horizontal semicircular canal. An investigation of this effect will soon be underway at the M.I.T. Man-Vehicle Laboratory facilities. Knowledge of this phenomenon might help in constructing visual displays and in enabling pilots to learn to correct more accurately for the reference drift or to reject it consciously.

APPENDIX A

The tables A.1 - A.5 present the frequency response data with standard deviations in tabular form. Table A.1 gives the composite data, presented graphically in Figs. 4.1 through 4.4. Tables A.2 through A.4 present individual subject data, which is also shown graphcially in Figs. 4.5 through 4.12. As in earlier figures, AR represents the amplitude ratio of the human operator's describing function, "phase" puts forth the describing function phase, and the "remnant" column gives that part of the human operator output uncorrelated with his input.

Table A.1

Tables of Human Operator Frequency

Response: Composite

Frequency rad/sec	AR ± 1 SD	Phase° ± 1 SD	Remnant volts x 105/rad^2	AR ± 1 SD	Phase° ± 1 SD	Remnant volts x 105/rad^2
		ROLL FHU			YAW FHD	
.14	.59±.15	16 ± 31	2	.34±.10	-5 ± 22	2
.21	.58±.12	15 ± 26	4	.49±.18	6 ± 30	4
.35	1.96±.49	23 ± 26	31	1.3 ± .3	10 ± 27	25
.63	4.0 ± .7	-16 ± 21	270	3.0 ± .7	-9 ± 22	170
.91	7.8±1.6	15 ± 11	330	5.7 ± .7	27 ± 9	200
1.5	9.8 ± .8	28 ± 4	320	7.8 ± .7	35 ± 4	350
2.2	12.1 ± .3	27 ± 3	200	10.3 ± .4	28 ± 2	520
2.7	14.5±1.4	18 ± 5	800	12.7 ± .8	18 ± 5	1200
4.3	18.9 ± .6	12 ± 1	6600	17.0 ± .5	12 ± 4	4400
7.7	30.1 ± .9	-11 ± 1	7000	23.6±1.3	-19 ± 4	3500
		ROLL FHD			YAW FHU	
.14	.43±.15	11 ± 27	5	.31±.10	8 ± 24	2
.21	.37±.08	-5 ± 31	2	.55±.17	-4 ± 29	4
.35	1.13±.42	13 ± 29	32	1.23±.30	11 ± 25	32
.63	4.2±1.1	-4 ± 19	80	2.7 ± .4	-20 ± 20	120
.91	5.2 ± .6	23 ± 9	200	5.1±1.1	27 ± 7	300
1.5	8.1 ± .8	24 ± 5	580	7.0 ± .6	29 ± 7	300
2.2	10.3 ± .5	26 ± 6	490	9.2 ± .5	25 ± 2	720
2.7	12.3±1.0	19 ± 7	1100	11.5±1.0	23 ± 6	3200
4.3	17.7±1.0	12 ± 1	5400	16.6 ± .8	12 ± 2	7600
7.7	25.6±1.5	-12 ± 2	7500	23.2±1.7	-15 ± 1	4000

Table A.2

Tables of Human Operator

Frequency Response: SU

Frequency rad/sec	AR ± 1 SD	Phase° ± 1 SD	Remnant volts × 105/rad^2	AR ± 1 SD	Phase° ± 1 SD	Remnant volts × 105/rad^2
	ROLL FHU			YAW FHD		
.14	.87±.58	8 ± 40	3	.27±.10	-18 ± 31	2
.21	.60±.24	17 ± 48	2	.39±.15	37 ± 47	5
.35	2.51±.81	33 ± 73	35	.64±120	22 ± 65	43
.63	3.45±1.03	1 ± 38	650	3.35±.138	-24 ± 25	84
.91	9.52±3.36	29 ± 19	630	6.93±.6	37 ± 19	165
1.5	10.6±.9	36 ± 8	340	9.0±2.0	44 ± 3	190
2.2	12.8±.4	29 ± 3	150	11.6±1.1	31 ± 4	140
2.9	16.4±1.7	23 ± 11	320	14.1±1.1	20 ± 10	500
4.3	19.7± 1.6	14 ± 3	2200	18.3±2.0	14 ± 2	1300
7.7	28.4 ± 1.0	-5 ± 2	6100	24.7±1.7	-6 ± 3	3100
	ROLL FHD			YAW FHU		
.14	.55±.53	27 ± 41	2	.32±.20	27 ± 54	1
.21	.50±.28	-14 ± 54	3	.49±.33	-20 ± 66	2
.35	1.78±1.58	38 ± 38	63	1.06±.38	22 ± 34	27
.63	4.18±1.85	20 ± 27	92	3.18±.88	21 ± 62	72
.91	5.30±.78	25 ± 9	180	4.3±1.9	42 ± 18	133
1.5	8.06±.70	28 ± 7	190	7.3±1.7	35 ± 13	420
2.2	10.6±.9	30 ± 3	170	9.6±1.3	34 ± 5	600
2.9	12.0±2.0	27 ± 10	570	9.6±2.1	35 ± 11	8100
4.3	18.1±3.4	15 ± 3	2800	16.9±1.4	17 ± 3	4700
7.7	25.9±2.6	-4 ± 4	3300	22.1±1.6	-9 ± 3	1900

Table A.3

Tables of Human Operator

Frequency Response: TI

Frequency rad/sec	AR ± 1 SD	Phase° ± 1 SD	Remnant volts × 105/rad^2	AR ± 1 SD	Phase° ± 1 SD	Remnant volts × 105/rad^2
	ROLL FHU			YAW FHD		
.14	.75 ±.07	24 ± 50	1	.41 ± .37	-22 ± 71	5
.21	.65 ±.32	42 ± 39	1	.50 ± .16	-47 ± 38	5
.35	1.42 ±.76	1 ± 34	8	1.6 ± .5	17 ± 39	26
.63	5.02 ±1.82	-25 ± 41	130	2.5 ± 1.6	-34 ± 48	330
.91	6.17 ±1.31	15 ± 3	80	5.7 ± 1.6	27 ± 5	57
1.5	10.8 ± .8	23 ± 9	120	8.0 ± 1.4	29 ± 7	270
2.2	12.7 ± .5	22 ± 5	260	9.9 ± .7	24 ± 1	260
2.9	14.8 ± .7	16 ± 5	500	11.3 ± 1.4	13 ± 6	280
4.3	19.2 ± .8	13 ± 2	1600	15.8 ± .4	10 ± 2	2700
7.7	32.2 ± 1.5	-5 ± 2	2600	23.7 ± 2.1	-19 ± 4	3100
	ROLL FHD			YAW FHU		
.14	.31 ± .16	4 ± 58	14	.37 ± .14	9 ± 39	1
.21	.34 ± .08	9 ± 75	2	.83 ± .47	15 ± 77	6
.35	.84 ± .34	43 ± 72	12	1.8 ± .6	-10 ± 62	52
.63	4.8 ± 2.5	1 ± 44	50	2.5 ± .8	-35 ± 27	300
.91	6.6 ± 1.5	27 ± 18	350	5.5 ± 3.1	40 ± 11	300
1.5	8.9 ± 1.4	23 ± 8	200	5.9 ± .7	21 ± 11	420
2.2	12.0 ± .8	18 ± 4	160	7.4 ± .9	22 ± 2	900
2.9	14.2 ± 2.2	9 ± 19	540	11.8 ± 1.5	12 ± 10	1700
4.3	18.3 ± .9	13 ± 3	4300	16.2 ± 1.0	11 ± 3	2600
7.7	32.2 ± 3.2	-6 ± 4	14000	23.7 ± 1.4	-11 ± 2	5900

Table A.4

Tables of Human Operator

Frequency Response: JG

Frequency rad/sec	AR ± 1 SD	Phase° ± 1 SD	Remnant volts × 105/rad2	AR ± 1 SD	Phase° ± 1 SD	Remnant volts × 105/rad2
	ROLL FHU			YAW FHD		
.14	.36 ± .02	20 ± 82	1	.43 ± .11	-13 ± 35	1
.21	.76 ± .27	0 ± 58	3	.69 ± .67	4 ± 84	5
.35	2.3 ± 1.3	27 ± 44	51	1.55 ± .93	27 ± 56	18
.63	5.2 ± 1.8	-5 ± 30	140	3.7 ± 1.6	34 ± 47	200
.91	9.9 ± 4.9	2 ± 36	330	5.7 ± 2.0	28 ± 21	360
1.5	8.8 ± 1.3	31 ± 6	320	7.7 ± .6	41 ± 10	230
2.2	12.1 ± 1.0	28 ± 2	150	10.0 ± .6	29 ± 4	280
2.9	13.5 ± 3.2	21 ± 8	670	14.4 ± 2.5	21 ± 10	1370
4.3	18.3 ± .5	10 ± 1	15000	16.8 ± .6	16 ± 16	4600
7.7	31.0 ± 1.3	-15 ± 2	5500	25.0 ± 2.3	-23 ± 4	5600
	ROLL FHD			YAW FHU		
.14	.69 ± .23	33 ± 66	2	.40 ± .33	0 ± 48	6
.21	.30 ± .06	-36 ± 58	1	.49 ± .25	5 ± 38	7
.35	1.13 ± .44	7 ± 66	42	.94 ± .41	19 ± 49	18
.63	4.9 ± 3.2	-16 ± 48	150	2.9 ± 1.0	-29 ± 25	30
.91	5.1 ± 1.3	41 ± 10	60	4.7 ± .8	11 ± 7	34
1.5	8.5 ± 2.7	28 ± 12	140	7.8 ± 1.2	31 ± 8	75
2.2	10.0 ± 1.1	26 ± 4	320	10.2 ± 1.1	24 ± 4	520
2.9	10.7 ± 1.2	22 ± 12	930	12.9 ± 2.3	19 ± 11	480
4.3	17.1 ± 1.4	10 ± 2	6700	17.5 ± 1.5	13 ± 3	14800
7.7	27.6 ± 4.1	-18 ± 4	2000	24.9 ± 6	-15 ± 3	3900

Table A.5

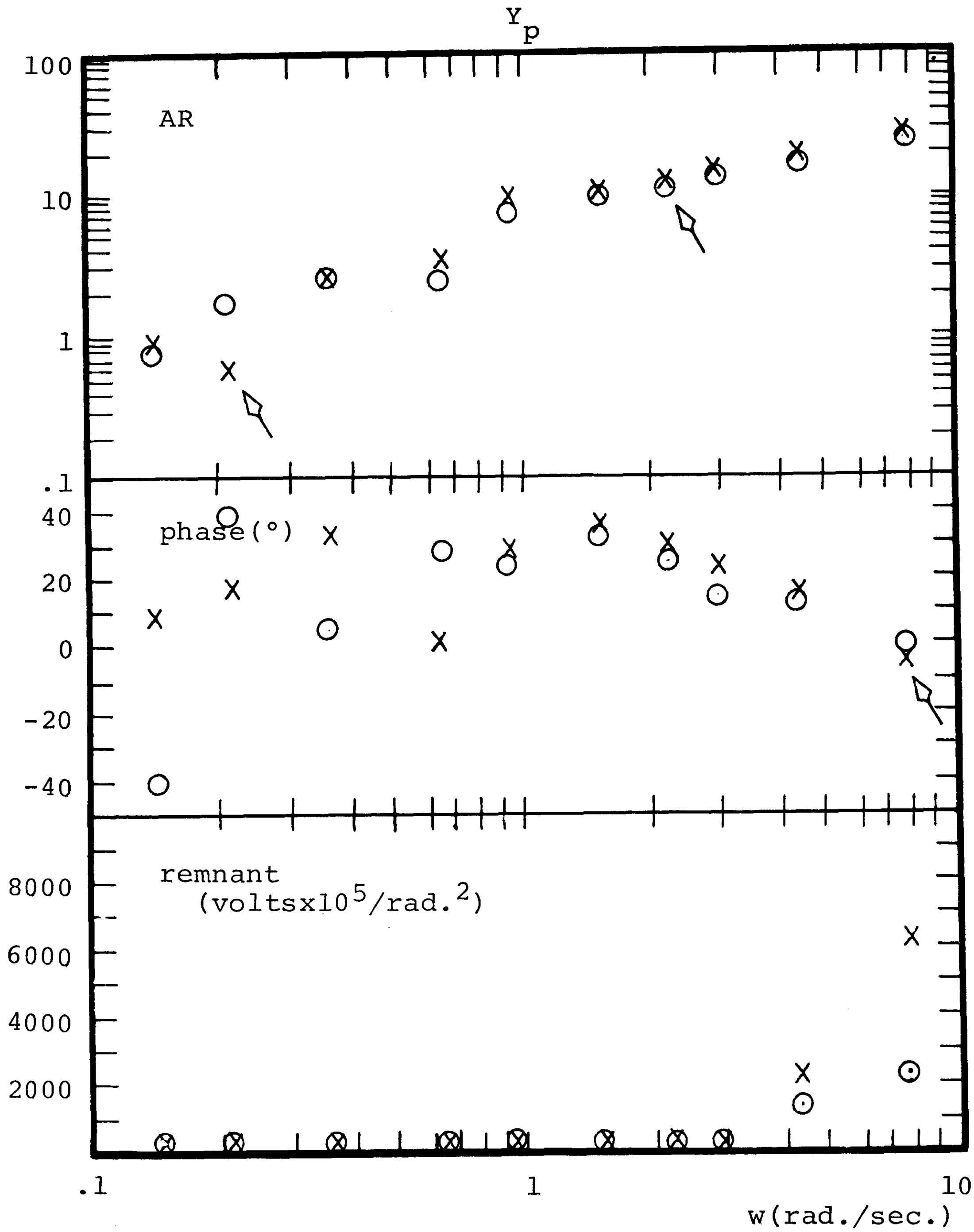
Tables of Human Operator

Frequency Response: BP

Frequency rad/sec	AR ± 1 SD	Phase° ± 1 SD	Remnant volts × 10^5/rad^2	AR ± 1 SD	Phase° ± 1 SD	Remnant volts × 10^5/rad^2
	ROLL FHU			YAW FHD		
.14	.38 ± .18	12 ± 69	2	.29 ± .11	33 ± 25	2
.21	.29 ± .10	1 ± 58	11	.37 ± .19	28 ± 57	3
.35	1.6 ± 1.0	32 ± 45	31	1.5 ± .6	-25 ± 54	15
.63	2.4 ± .6	-35 ± 58	180	2.2 ± .8	-12 ± 51	66
.91	5.7 ± 1.4	14 ± 16	310	4.5 ± .6	10 ± 22	220
1.5	8.8 ± 2.7	20 ± 9	480	6.4 ± .8	24 ± 11	700
2.2	10.8 ± .7	27 ± 10	240	9.6 ± .5	27 ± 2	1400
2.9	13.3 ± 4	13 ± 16	1900	11.1 ± .7	18 ± 14	2600
4.3	18.3 ± 1.3	10 ± 3	7600	17.0 ± .4	9 ± 5	9100
7.7	28.8 ± 3	-18 ± 2	14000	20.8 ± .4	-29 ± 13	3300
.14	.18 ± .09	-21 ± 46	1	.15 ± .05	-3 ± 52	2
.21	.35 ± .12	20 ± 59	4	.37 ± .23	-15 ± 48	3
.35	.79 ± .26	-37 ± 47	10	1.1 ± .9	12 ± 52	32
.63	2.8 ± .86	-22 ± 26	32	2.2 ± .7	-35 ± 36	65
.91	3.7 ± 1.2	-2 ± 29	240	5.9 ± 2.1	13 ± 17	760
1.5	7.0 ± .7	15 ± 9	1800	7.0 ± 1.1	27 ± 22	280
2.2	8.6 ± .8	31 ± 22	1300	9.7 ± .6	21 ± 6	860
2.9	12.4 ± 2.1	17 ± 9	2300	11.6 ± 2	25 ± 15	2600
4.3	17.2 ± 1.2	11 ± 3	7800	15.7 ± 2	7 ± 4	12500
7.7	25.8 ± 1.0	-20 ± 3	11000	22.2 ± 2	-24 ± 2	4500

APPENDIX B

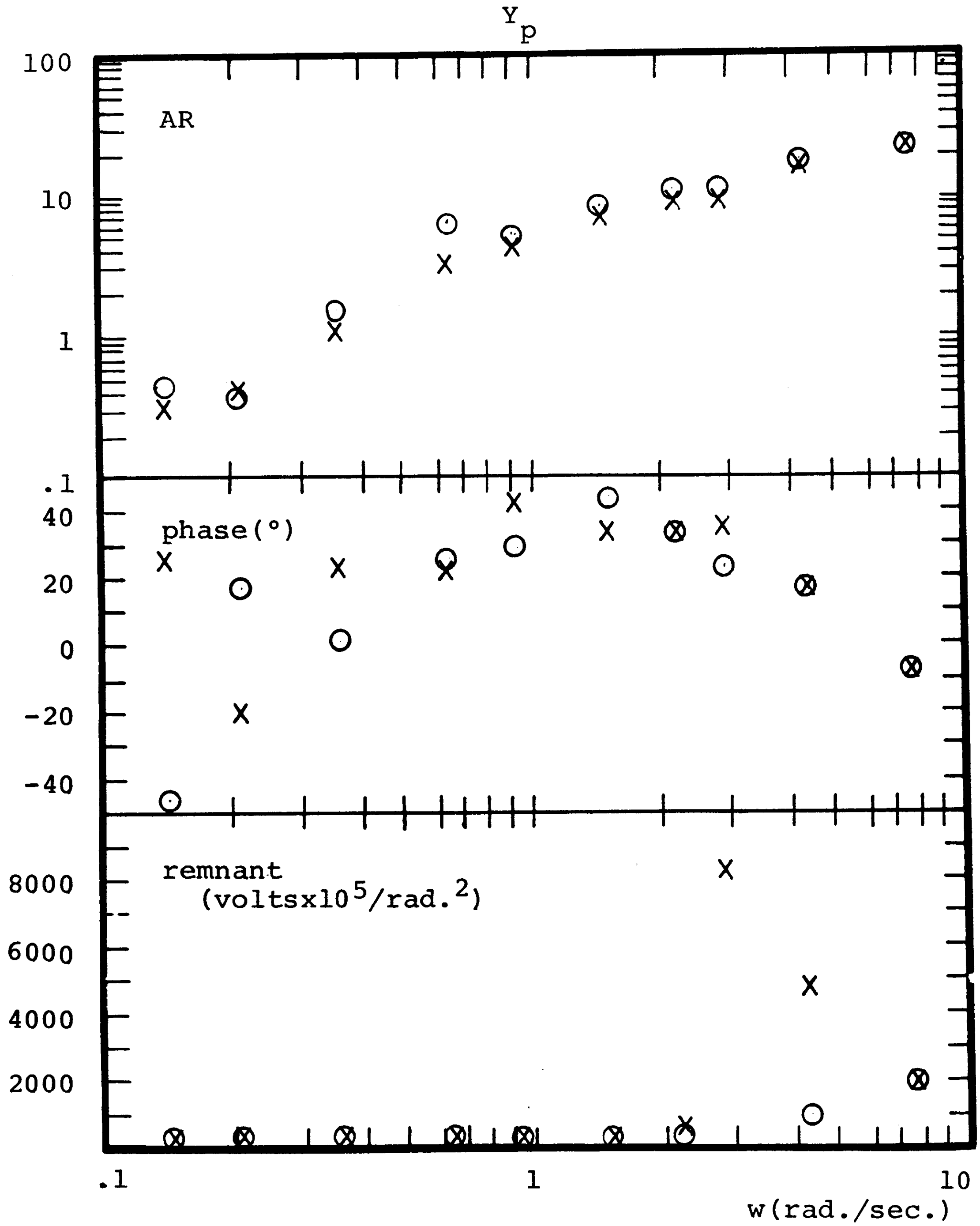
Graphs of control experiments referred to in section 4.6 are presented in Figs. B.1 through B.5. The first four figures refer to the effect of fixing head position and indicate only slight improvement in performance for the head position fixed as compared to head position free. Figure B.5 is included to indicate the effects of visual cues (motion only vs. motion plus vision).



SU: ROLL FHU and ROLL HUU

X ROLL FHU, mean rISE=.06
O ROLL HUU, mean rISE=.22
Statistically significant difference ($p < .05$)

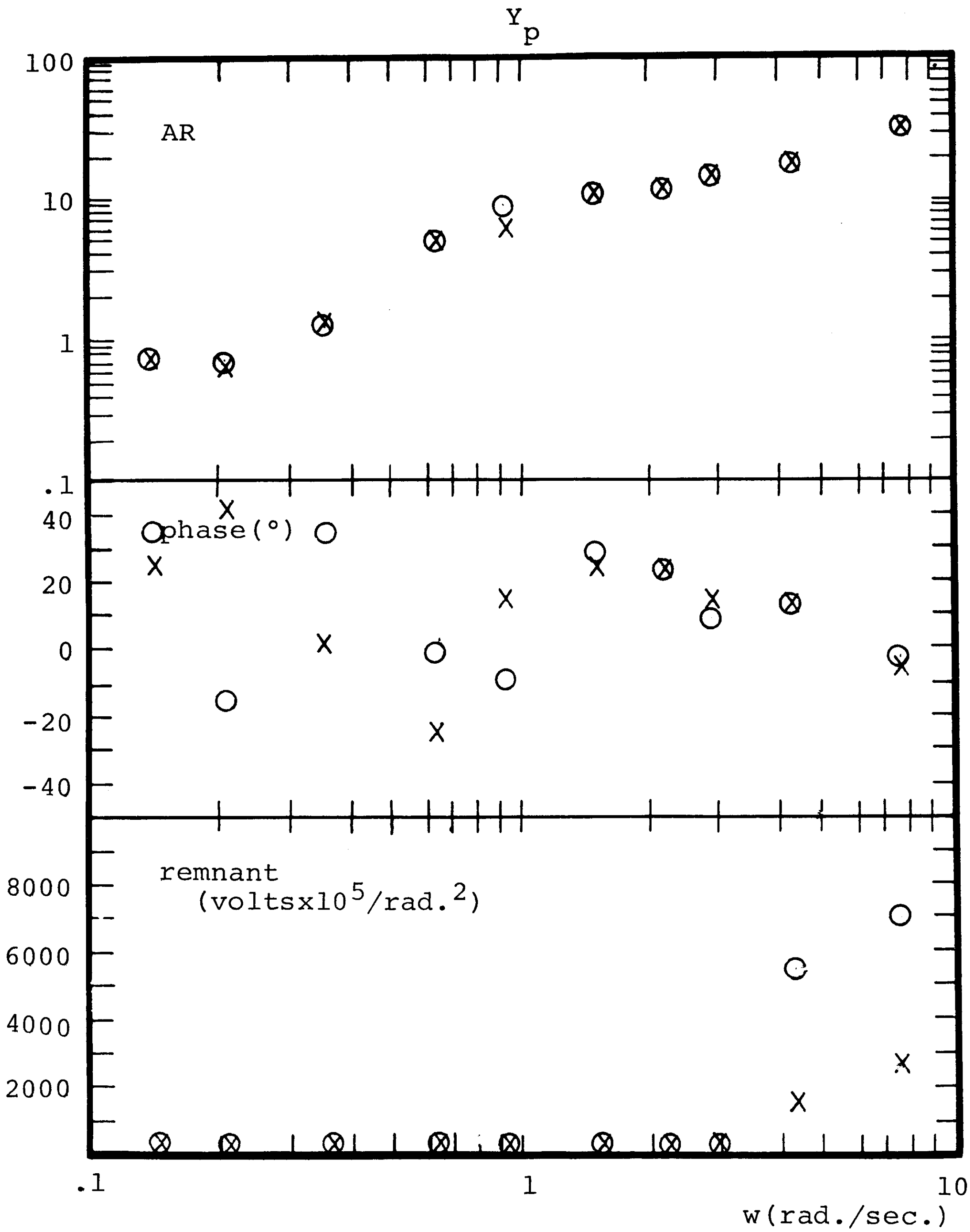
Figure B.1



SU: YAW FHU and YAW HUU

X YAW FHU, mean rISE=.23
O YAW HUU, mean rISE=.15
Statistically significant difference (P < .05)

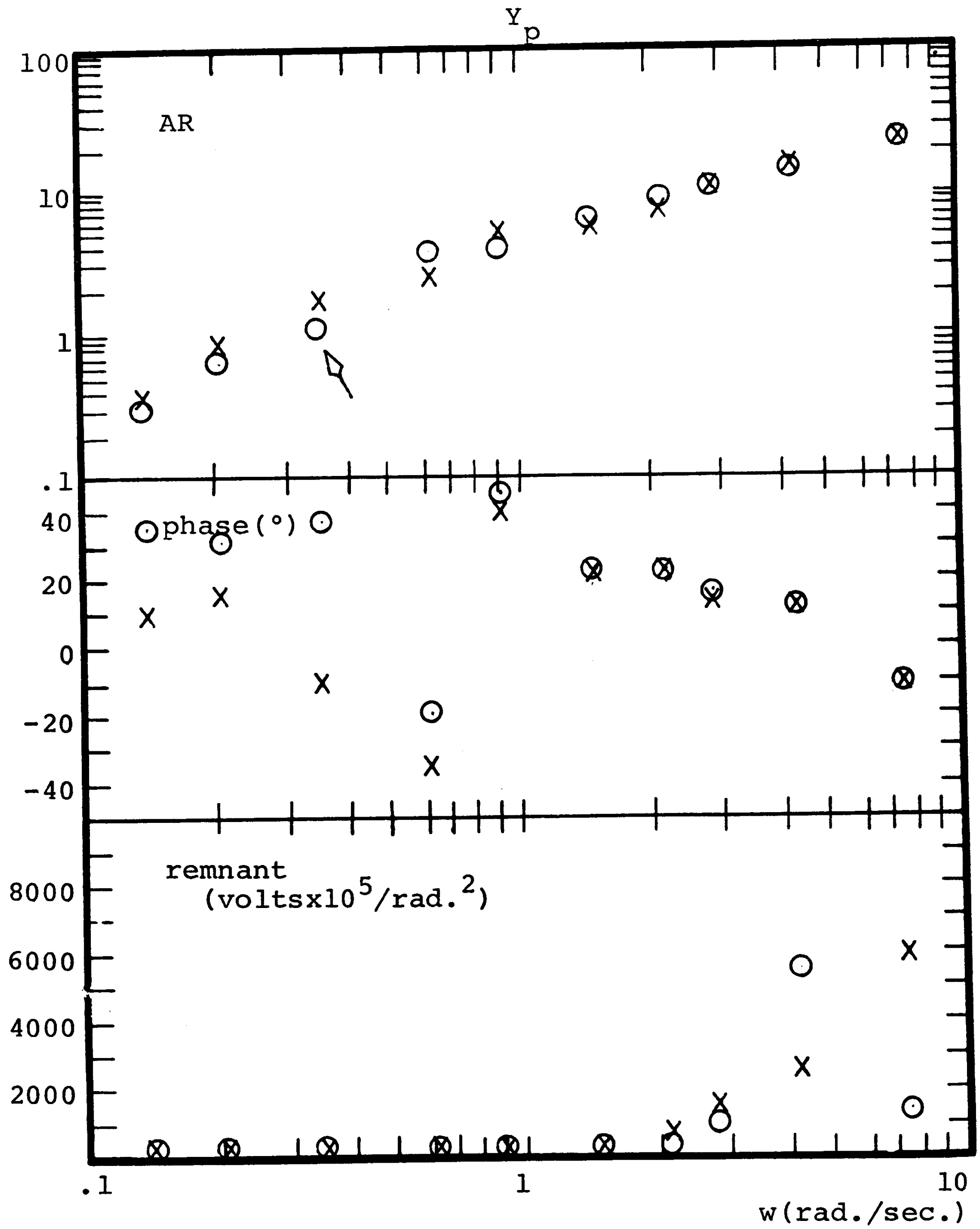
Figure B.2



TI: ROLL FHU and ROLL HUU

X ROLL FHU, mean rISE=.11
O ROLL HUU, mean rISE=.13
Statistically significant difference ($P < .05$)

Figure B.3



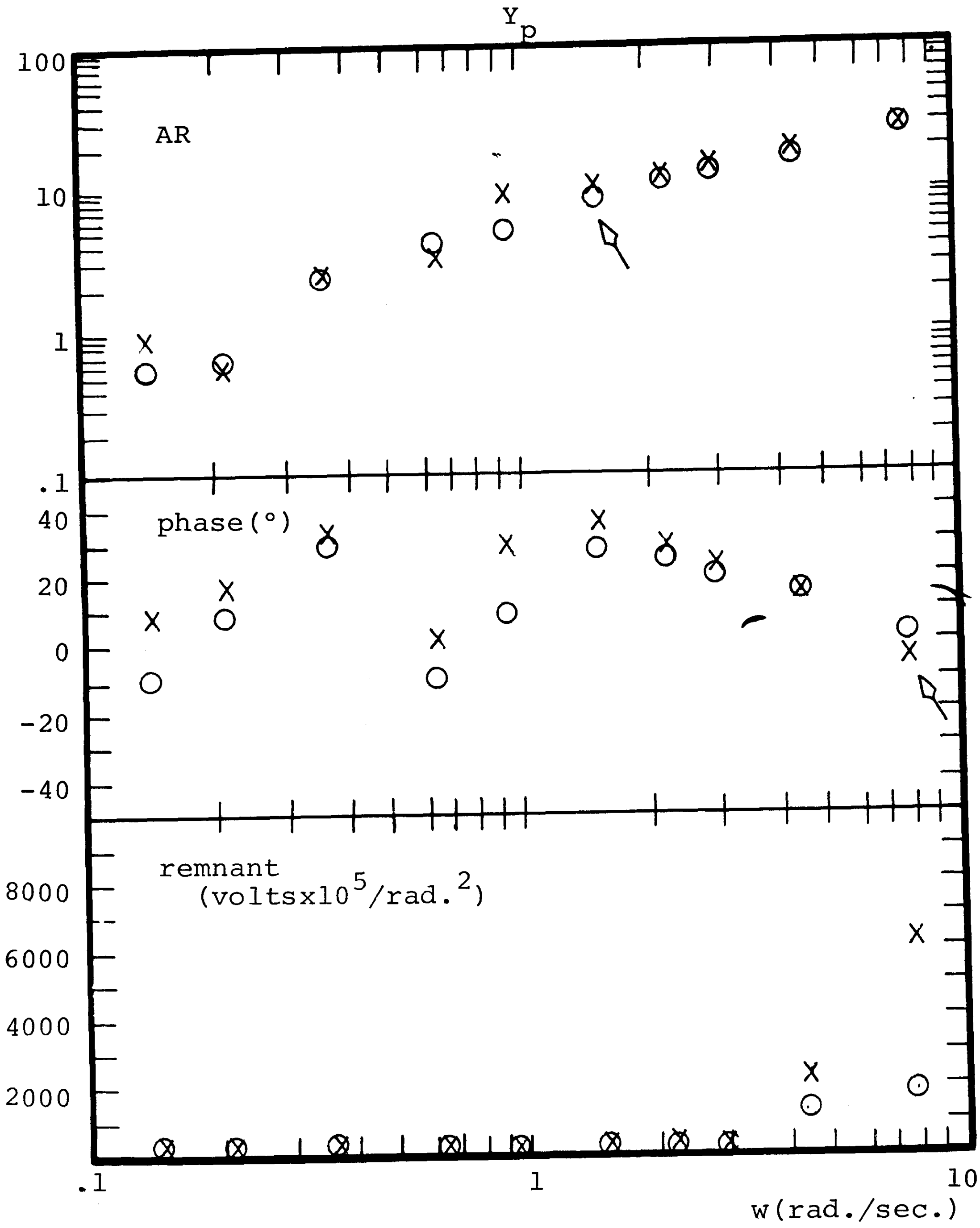
TI: YAW FHU and YAW HUU

X YAW FHU, mean rISE=.25

O YAW HUU, mean rISE=.3]

Statistically significant difference (P < .05)

Figure B.4



SU: ROLL FHU and ROLL FHU(motion only)

X ROLL FHU, mean rISE=.06
O ROLL FHU(motion only), mean rISE=.15
Statistically significant difference (P < .05)

Figure B.5

REFERENCES

1. Romer, A. S., The Vertebrate Body, W. B. Saunders Co., Philadelphia, 1967

2. Ciba Foundation Symposium, Myotactic, Kinesthetic and Vestibular Mechanisms, Ed. by A. V. S. de Reuck and J. Knight, Little, Brown and Co., Boston, 1967

3. Gray, Gray's Anatomy, Thirty-third edition, Longmans, Green and Co., 1962

4. Young, L. R., "A Control Model of the Vestibular System," International Federation of Automatic Control Symposium on Technical and Biological Problems in Cybernetics, Yerivan, Armenia, U.S.S.R., September 1968

5. McRuer, D. T., Hofmann, L. G., Rex, H. R., Moore, G. P., Phatak, A. V., Weir, D. H., Wolkovitch, J., "New Approaches to Human Pilot/Vehicle Dynamic Analysis," Technical Rept. AFFDL-TR-67-150, February 1968 (Table IV, page 25)

6. Stapleford, R. L.,"Multimodality Pilot Model for Visual and Motion Cues," Fourth Annual NASA-University Conference on Manual Control, Ann Arbor, Michigan, March 1968

7. Lowenstein, O., "The Functional Significance of the Ultrastructure of the Vestibular End Organs," Second Symposium on the Role of the Vestibular Organs in Space Exploration, NASA SP-115, January 1966

8. Guedry, F. E.,"Comparison of Vestibular Effects in Several Rotating Environments," Symposium on the Role of the Vestibular Organs in Space Exploration, NASA SP-77, 1965

9. Benson, A. J., and Bodin, M. A., "Interaction of Linear and Angular Acceleration on Vestibular Receptors in Man," Aerospace Med., 36:144-58, 1966

10. Young, L. R., "Effects of Linear Acceleration on Vestibular Nystagmus," Third Symposium on the Role of the Vestibular Organs in Space Exploration, January 1967

11. Shirley, R. S., "Motion Cues in Man-Vehicle Control," M.I.T. Sc.D. Thesis, January 1968

12. Meiry, J. L., "The Vestibular System and Human Dynamic Space Orientation," M.I.T. Sc.D. Thesis, June 1965

13. Young, L. R., "Some Effects of Motion Cues on Manual Tracking," J. Spacecraft and Rockets, Vol. 4, #10, October 1967

14. Ciba Foundation Symposium, Touch, Heat and Pain, Ed. by A.V.S. de Reuk and J. Knight, Little, Brown & Co., Boston, 1966

15. Young, L. R., and Graybiel, A., unpublished

16. McRuer, D. T., Graham, D., Krendel, E., Reisener, W., "Human Pilot Dynamics in Compensatory Systems," Tech. Rept. No. AFFDL TR-65-15

17. McNemar, Q., Psychological Statistics, Wiley, 1962