FUNDAMENTALS of SIMULATION

Frank M. Cardullo
State University of New York
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Introduction

Flight and ground vehicle simulation can be defined as the representation of vehicle and system dynamic characteristics with varying degrees of realism for research, design, training or entertainment purposes. The "representation" is usually in the form of analytic expressions programmed on a digital computer. Vehicle simulation may be performed with or without a human operator in the loop. The human in the loop imposes additional constraints on the simulator such as requiring a means for the operator to control the simulated vehicle in a manner consistent with the means provided in the vehicle being simulated. It requires simulation of the environment to an extent appropriate for the purposes of the simulation, and it further requires that all events in the simulator occur in real time. Real time is a term, which is used to denote that all time relationships in the simulator are preserved with respect to what they would be in the airplane in flight.

Research simulators are usually employed to determine patterns of human behavior under various workloads or in response to different instrument display configurations or different vehicle dynamic characteristics. Design simulators are used to conduct tradeoff studies to evaluate different design approaches in the vehicle. Virtually all aircraft and automobile manufacturers in the United States employ simulators, to a very large extent, in the design process. These simulators may cost millions of dollars. While the investment is substantial, many hours of vehicle testing are saved and designs can be evaluated within the production schedule, consequently, saving many dollars in retrofitting hardware. Simulators are also used by the aircraft manufacturer to demonstrate aircraft characteristics to potential customers well before first flight of a new airplane.

The third, and currently most pervasive, use of flight simulators is for training operators of the aircraft and its systems and maintenance personnel. The flight simulator was first patented in 1929 by Edwin A. Link to train pilots in instrument flying. His device was subsequently dubbed the "Pilot Maker" and was responsible for training a half million pilots during World War II. The current flight simulator is substantially different from Link's Blue Box and is currently being used to train pilots of virtually every military and commercial aircraft in the US and Europe.

Aircraft training Simulators are broken down into four categories: operational flight trainers (OFT), these devices are used to train pilots, copilots, flight engineers and navigators as appropriate in all aspects of flying a modern aircraft either as a full crew or a pilot alone. A second type of device is a Weapons Systems Trainer (WST) employed on tactical and strategic aircraft, which essentially adds the aircraft's offensive and defensive systems to the flight systems of the OFT. A third category is the part task trainer (PTT) which is used to train flight crews on specific tasks such as air refueling. Finally, Maintenance Trainers (MT) are employed to train mechanics and technicians in the diagnosis of problems and the procedures of routine maintenance on various aircraft systems such as engines, flight controls, radar, etc.

Training Simulators have been used extensively by NASA for training astronauts in programs from Mercury to the Space Shuttle. They were also used to verify procedures and flight program modifications during the Apollo XIII mission which might have ended in disaster after an in-flight explosion partially disabled the spacecraft.

In civil aviation, flight simulators are used extensively to transition pilots from one aircraft type to another. The Federal Aviation Administration (FAA) allows pilots to perform transition training entirely in a simulator, provided the simulator meets the requirements of AC120-40B (revision c has been awaiting promulgation for quite some time). This document defines four levels of airplane simulators (A through D) of increasing fidelity. In addition, the FAA allows credit for training in so called Flight Training Devices (FTD). The FAA publication AC120-45A specifies the requirements for these devices in seven levels (1 through 7) of increasing fidelity. Furthermore, the FAA has published requirements for qualifying rotary wing simulators employed in civil aviation. These requirements are presented in the FAA Advisory Circular AC120-63.

Training simulators are not yet used as extensively in ground vehicles as they are in air vehicles. However, there is considerable utilization in armor vehicles and considerable application in truck driving and ship piloting. The future will bring applications in heavy construction equipment, emergency vehicle and other nonstandard passenger vehicle training. Many states are considering requiring testing of certain segments of the driving population, e.g. the elderly, periodically, in simulators. Dangerous situations can be presented in a safe environment to test driver reactions.

That aircraft training simulators save substantial amounts of money in fuel costs, expenditure for weapons, etc. is obvious. However, the simulator has much greater benefit in that it is, in many cases, a better training device than the aircraft. This is true because of the safety, versatility and speed with which critical maneuvers may be performed. For example, in practicing landing in an aircraft, a student pilot may make an approach to either a touch and go landing or a full stop landing or perhaps a missed approach. He then must contend with air traffic and weather to reenter the landing pattern for another attempt. This takes considerable time, whereas in the simulator, after landing the simulated aircraft, the instructor may reset to the approach configuration at the top of the glide slope ready to go again in seconds. The simulator also allows the student pilot to learn to deal with malfunctions in a safe environment. Practicing engine out approach and landing is very useful but also very dangerous to perform in the airplane. The simulator provides an excellent training medium for this and many other malfunctions.

In 1990 Senator Nunn recommended spending more than $2 billion on simulation in the following several years in order to save tens of billions through reduced readiness training with operational equipment. The importance of simulation and the breadth of its applications have been recognized by a Department of Defense (DOD) task force on simulation. They recommended the formation of a high level DOD simulation oversight committee for the development and use of simulation in the areas of; research and development, requirements' definition, test and evaluation, and training and rehearsal. This activity has resulted in the expansion of simulation into many non flight areas such as ground forces, air traffic control, air warfare control, etc.

The Army's Comanche program is an example of how flight simulation was applied to all of the above areas. Two competing industry teams used their own simulators to conduct R&D on their proposed aircraft characteristics, avionics options, sensor capabilities and weapons configurations. They were striving for a winning proposal that balanced performance and cost and the ability to demonstrate that system in the simulator without having to build the airframe integrated with the avionics, sensors and weapons. The Army, at its Ames Research Facility, used their flight simulators to define requirements for the Comanche and requirements for testing the industry proposals. The industry teams' simulators allowed Army evaluators to assess each team's system design in a simulated tactical operational manner without having to build the helicopter or provide the test facilities and ranges. The program called for the winning team to evolve its simulator into the Combat Mission Simulator required for the training system when the system goes to production. The quality and capability of individual flight simulators have improved sufficiently to allow simulation to be used extensively for high-ticket programs such as the Comanche.

DARPA demonstrated through the SIMNET program how networks of hundreds of moderate cost ground vehicle simulators could investigate tactics and equipment options in battle group exercises. In the future low cost simulators may have sufficient capability to allow their use for any system development and deployment. However, to accomplish this we must move beyond the expensive custom development of each flight simulator. We have to be able to readily assemble a simulator out of interfaceable modules both hardware and software. Until the future of low cost "tinker toy" simulators arrives, we must justify the cost of each simulator developed. Historically, the reasons a simulator gets built starting with the easiest to justify are; it's the only option, safety, availability, economy, efficiency, or effectiveness. The SIMNET program has led to the Distributed Interactive Simulator (DIS) concept and the advent of the full battlefield simulation employing perhaps thousands of linked entities including ground troops.

A simulator can sometimes be the only option. Training astronauts for landing the lunar module on the moon could only be done in a simulator. Nuclear reactor simulators are the only acceptable manner to train operators to manage reactor emergencies.

Safety in flight simulators is an automatic advantage over an actual flight at all times. Some years ago commercial transport check rides in the aircraft to certify airline pilots for ability to handle engine out on take-off emergencies resulted in an unacceptable loss of aircraft, crew and FAA certifiers. This certification check was transferred to the simulator and eliminated from the aircraft. The Navy requires night carrier landing training in flight simulators prior to carrier deployment of aircrews. All military services require concurrent deployment of training simulators with the introduction of new aircraft to minimize the high accident rates that previously occurred with new aircraft introduction.

Availability of a vehicle simulator is not a function of the outside weather and almost instantly any simulator weather condition can be obtained. An aircraft is typically flight worthy 500 hours per year. A simulator can be available 2000 hours per year and can be operated 4000 hours per year, or more with extra shifts.

The economy factor of flight simulator operation to aircraft operation is typically 10% to 20%. After the FAA certified flight simulators for airline pilot check rides and training, the airlines were able to amortize the cost of the simulator in less than two years through flight operations savings. To practice landing approaches, a simulator can be instantly reset to the starting point after landing instead of having to fly the aircraft back to the starting point. The efficiency of simulators applies to both testing and training. If you want to test or train dive-bombing, most of the aircraft flight time is consumed by taxi, takeoff, flight to the test/training area and return. With a simulator you can initialize at the test area and make as many bombing runs as desired with no ordnance cost or range safety problems.

According to some observers, effectiveness of flight simulators usually falls short of the aircraft. They state that the best a simulator could be, is as effective as the aircraft. This perspective is disputed by many that feel that simulators actually provide better training than the actual vehicle for many tasks. Another perspective is embodied in the concept of Military Value. There is evidence that military pilots who survive their first ten combat engagements have a much higher likelihood of survival in following engagements than a pilot on his first combat experience. If 10 or even 50 combat engagement experiences in a simulator cause a significant reduction in an actual combat attrition rate, then the simulator has Military Value. For the pilot who would not survive the first ten combat engagements in the aircraft, he would find the simulator more effective than the aircraft since the aircraft couldn’t prepare him in time to survive to fight again.

Anatomy of a Human in the Loop Simulator

In discussing the components of a human in the loop simulator it is important to have some background in the discipline of man-machine systems. A brief discussion is presented in an appendix to this section.

Figure 1 illustrates the major components of a piloted flight simulator (a ground vehicle simulator would have similar components). While the illustrated simulator is an aircraft simulator, the major components are essentially the same for all human in the loop simulators. The primary component is the cab with operator controls and instruments. The other elements are the visual display system which replicates the out the window scene, the force and motion cuing system with provide the bodily sensations of the motion of the simulated vehicle, the sound system which provides the normal and abnormal sounds associated with the simulated vehicle, the instructors’ and/or experimental station which provides the control of the device, and the computer system which drives the entire complex.

The operator of the simulated vehicle manipulates the controls in the simulator cab in the same manner he would in the vehicle. Sensors in the control system measure this control manipulation and transmit the information of the simulator computer system whereupon the appropriate dynamics of the simulated vehicle are computed by the algorithms in the computer system. These dynamics are then used by the cockpit instrument drive algorithms to provide the appropriate commands to each of the instruments indicating the state of the simulated vehicle including its engines and other systems. The vehicle state information is also used by the simulator visual system to display the

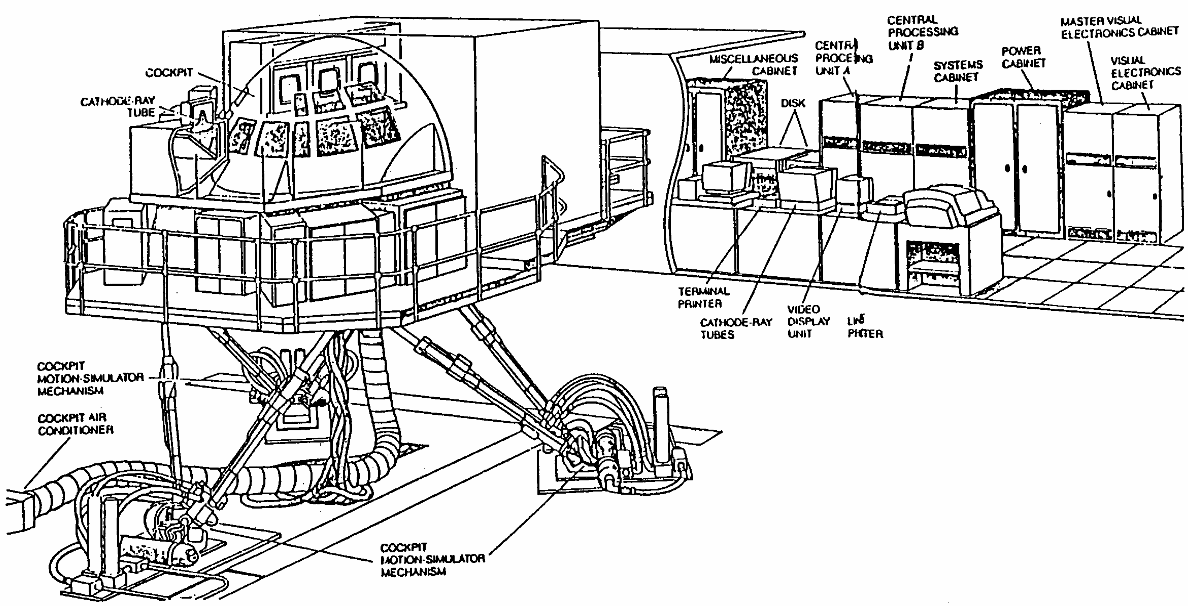

Figure 1

resulting out the window imagery and by the simulator motion systems to provide the appropriate motion cues. The sound system also is driven by the vehicle and system state information. Algorithms in the computer also determine the proper force, which should be felt by the operator due to the dynamic effects on the control devices. The calculated force is then transmitted to a hydraulic or electric force feel system at the cab, which alters the forces, experienced by the crewmember.

Simulator Software

A key element in this simulation process is the software, which controls and performs the simulation. Figure 2 illustrates the software found in a typical simulator and also shows the hardware interfaces. The simulator software comprises three parts; the system software, the instructional and/or operators' software, and the math models, which simulate the various vehicle functions. The system software includes the real time operating system, input/output processing task scheduling, etc. The instructional software is utilized only by training simulators and provides the features necessary for training such as performance monitoring, record and playback of various scenarios, maneuvers demonstration, etc. The operators' software allows the various modes of the simulator to be exercised such as a freeze, which stops the action in place; reset which allows the operator/instructor to position the vehicle at predetermined locations in space; fast time/slow time which allows for faster or slower than real time operation. Finally, the software contains the simulation math models.

Mathematical models are required of the vehicle dynamics, the engines, control system, the avionics systems, weapon systems, the atmosphere, vehicle systems such as electrical, hydraulic, fuel management, etc. A mathematical model is a set of mathematical equations, which describe the behavior of a physical system. Figure 2 illustrates the type of mathematical models typically found in a vehicle simulator and the information flowing among the various modules. The dashed lines enclose the portion of the simulator, which is implemented in software. The area to the right represents hardware at the cab and the area to the left is the instructors' and/or operator station (IOS).

The vehicle dynamics simulation comprises the math models contained within the innermost (crosshatched) area of Figure 2, in this case for an aircraft simulator. However, the diagram would be very similar for any vehicle simulator, although perhaps more complicated for an automobile or truck. The flight controls module senses the crew's control activity and interprets it as control device deflections or engine commands. These parameters are then passed on to the appropriate modules such as the aerodynamics module or the engine module. The engine module contains the simulation of the engine that is installed in the particular vehicle being simulated. The output of this module is the thrust of each engine, which ultimately contributes to the forces and moments acting on the airplane, in this case, also the RPM, fuel consumption and other engine parameters, which are displayed in the cockpit.

The aerodynamics module computes all the aerodynamics forces and moments acting on the aircraft as a result of control actions by the pilot and the aircraft's interaction with its environment. The forces are drag, side force and lift. The moments are rolling moment, pitching moment and yawing moment.

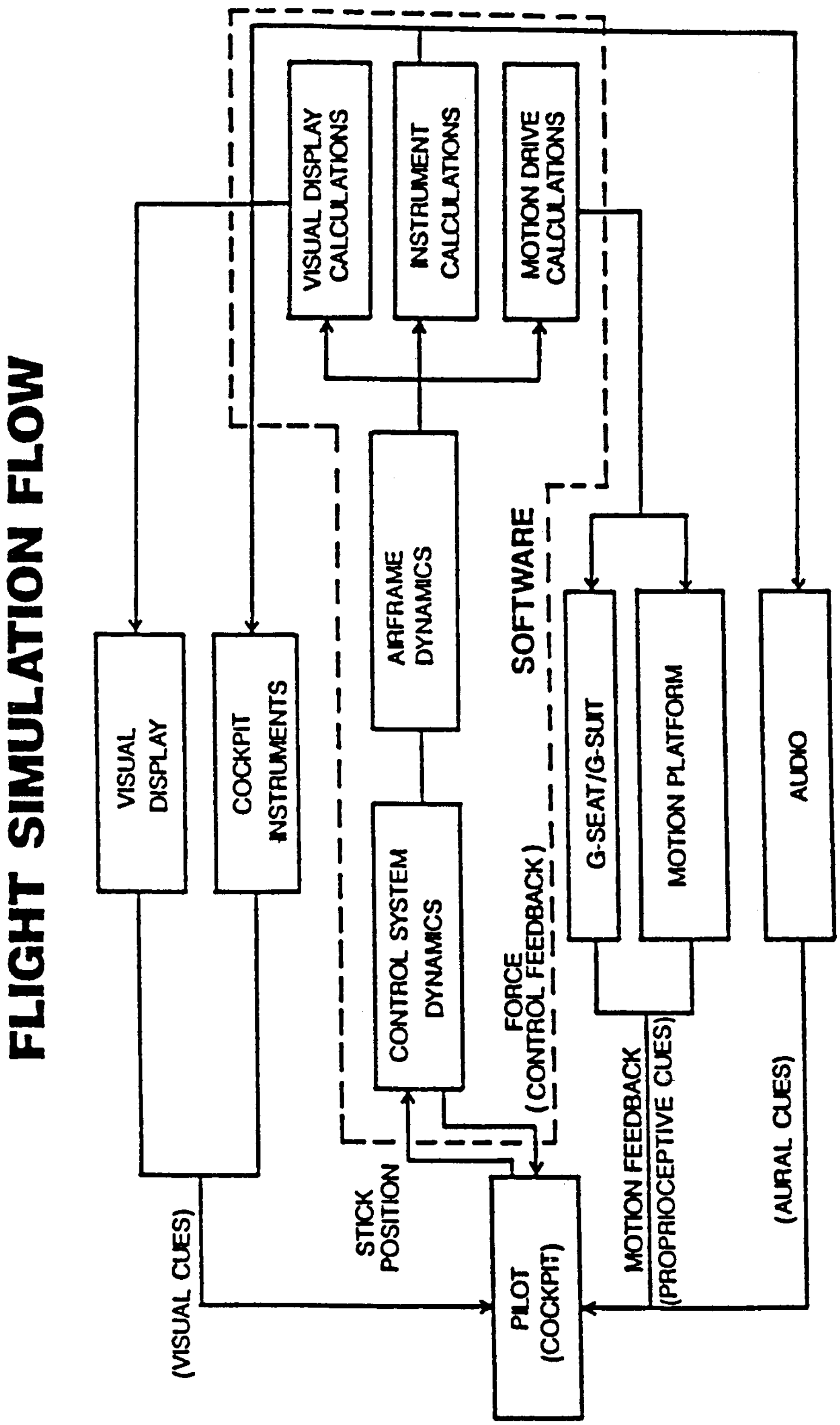
FLIGHT SIMULATION FLOW
VISUAL DISPLAY
COCKPIT INSTRUMENTS
VISUAL DISPLAY CALCULATIONS
INSTRUMENT CALCULATIONS
MOTION DRIVE CALCULATIONS
AIRFRAME DYNAMICS
CONTROL SYSTEM DYNAMICS
SOFTWARE
G-SEAT/G-SUIT
MOTION PLATFORM
AUDIO
FORCE (CONTROL FEEDBACK)
STICK POSITION
(VISUAL CUES)
PILOT (COCKPIT)
MOTION FEEDBACK (PROPRIOCEPTIVE CUES)
(AURAL CUES)

Figure 2

The landing gear model computes the forces and moments acting on the aircraft as a consequence of the interaction of the airplane and the ground in taxiing, landing and taking off. The mass properties module computes the vehicle mass and location of the center of gravity as well as the moments of inertia.

The output of these four modules is used by the equations of motion module to compute the simulated aircraft state vector, which defines its location in space (latitude, longitude, and altitude) and its orientation relative to the ground (pitch, roll and heading). It also includes velocity and acceleration components measured with respect to the body axes of the aircraft. The manner in which this is accomplished is by summing the forces and moments due to engines, aerodynamics, landing gear and weight, then computing the acceleration components which are then integrated to obtain velocity components which are then integrated to obtain the spatial coordinates and orientation of the vehicle relative to the ground.

As is illustrated in Figure 2, the simulated aircraft state vector is passed to various other software modules which utilize it to simulate other aircraft systems or to drive cuing systems such as visual, motion and sound. The Navigation and Communication module simulates the aircraft's navigation aids, landing aids and various communication devices. The electronic warfare simulation may actually be composed of several modules distributed between offensive systems and defensive systems, which may also contain mathematical models of threats such as other aircraft or missiles.

It can be seen in Figure 2 that these software modules interface with hardware systems, which provide cues to the pilot to enable him to control the simulated aircraft as he would the real aircraft. In most cases, the cuing devices synthesize the cues; therefore, the corresponding software modules contain algorithms to effect that synthesis.

Visual Simulation

The visual and radar modules, in modern vehicle simulators format the aircraft state vector and environmental information, which are then passed to the image generator. The image generator employs sophisticated computer graphics techniques to generate imagery for either a radar display or to create the view the crew would have out the windows of the vehicle. Once the image is calculated, it must be displayed. The display system usually involves some method of projection and a viewing surface. For real image systems, the display surface is a screen. For a virtual image system, the display surface is a mirror.

Motion Simulation

Also shown in Figure 1, below the cab is a platform supported by six hydraulic actuators in this case, which are controlled by the motion system software to provide cues to a pilot of his motion environment. While these motion systems are capable of providing motion in all six degrees of freedom, in which the vehicle moves that motion is constrained by the physical limitations of the actuator size and geometry. Therefore, highly sophisticated drive algorithms are required in the software to provide usable cues to the pilot and eliminate false cues. Flight simulators frequently use ancillary motion cuing devices such as seat vibrators to simulate stall buffet and other vibratory motion. In addition, G-Seats are sometimes employed to provide sustained cues by stimulating pressure sensations across the back and buttocks of the pilot in the simulator. The anti-g suits commonly found in high performance aircraft are frequently utilized in simulators of these types of aircraft to assist the pilot in withstanding high g stress, and these have been found to produce very effective cues.

Sound Simulation

Modern simulators often include sound simulation, which is achieved by software control of digital sound synthesizers. These systems are capable of reproducing all aircraft sounds such as engine sounds, aerodynamic noise, landing gear and flap deployment, etc. In addition, messages can be given to pilots from simulated air traffic controllers, on board warning systems or maneuver critiques from a surrogate controller.

Vehicle Instrument Simulation

All or some of the myriad of instruments are simulated, depending on the purpose of the simulator. Until recently, simulator instrument panels were cluttered with numerous dials, indicators, switches, lights and other devices by which the status of the simulated vehicle's system could be monitored and controlled, reflecting the vehicle being simulated. Each of these devices was under computer control. However, modern aircraft have replaced many of these instruments with video display units and the buttons, knobs and switches by computer keypads. Hence, the aircraft simulator has followed suit, thereby, simplifying the cockpit hardware substantially.

Control Loading System

This system is attached to the vehicle's control devices through mechanical linkages and servomechanisms and ensures that the operator feels the correct forces on the controls as he maneuvers the vehicle through its performance envelope. Originally consisting of a system of springs, control-loading units are now exclusively hydraulic or electric and often include their own microprocessor system.

Computer

The digital computer is at the very heart of the vehicle simulator and literally is responsible for every single event that occurs. Progress in simulator development over the last 20 years may be comprehended if we note that a typical simulator of the earlier vintage would have a single central processor and probably only 32K of memory. Today, high fidelity and the complexity of the advanced training system calls for multi processor configurations with incredibly large amounts of memory for program and data storage. The computer communicates with the simulator hardware through a real time interface consisting of analog to digital and digital to analog converters. Distributed microprocessor systems seem to be the future trend for training simulators.

Simulation Validation

For simulators to be effective research, design or training devices, their performance must be validated against the vehicle being simulated to the extent required for the mission of the simulator. This is frequently accomplished by ascribing tolerances to the simulator performance with respect to vehicle test data for the vehicle dynamics simulation and other test data for other systems.

Virtual Reality

What is virtual reality? It is nothing more than man-in-the-loop simulation. It is not a new technology but rather a technology that has been used for more than 60 years and is, at most, being used in new applications such as entertainment, education, architecture, etc. Some "virtual reality" practitioners claim the distinction lies in the "immersion of the individual in the scene". This, of course, has been accomplished in vehicle simulators for quite some time. Perhaps the uniqueness lies in the fact that the visual scene is presented at the subject's head. The use of head mounted displays has been employed, albeit not in very great numbers, in flight simulation. In fact, the technology employed in most "virtual reality" devices is at a lower level of fidelity. This is a consequence of attempting to achieve a low cost for entertainment devices.

To this observer, the term virtual reality is an oxymoron. Considering the definitions from geometrical optics, a virtual image is one, which is not actually located where it appears to be, while a real image is where it appears to be. Consequently, it seems that "virtual environment" would be a more precise term by which this technology may be designated.

Nevertheless, whatever moniker is given to the technology, the entertainment embodiment is the fastest growing application of simulation technology today. One other non-traditional application lies in education, where high school and college science experiments may be conducted in a virtual laboratory. Another would be for surgeons to train for new procedures on virtual patients. They could even rehearse patient specific procedures with visual data bases developed from diagnostic digital databases such as MRI, CAT, sonography, etc.

ACKNOWLEDGMENT

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APPENDIX

Human-in-the-Loop Systems

Vehicle simulators are one application of the discipline of human-machine systems. Therefore, it is appropriate to introduce some of these concepts at this point. A man-machine system can be considered as any closed loop system with the loop being closed through the human operator. The study of man-machine systems is differentiated from ergonomics and human factors in that it deals with only dynamic systems and is treated as a systems engineering problem. Figure 1 illustrates the block diagram of a human in the loop system. Notice that it differs from the classical closed loop control system in that there is a human in the feedback path and the controller is a human.

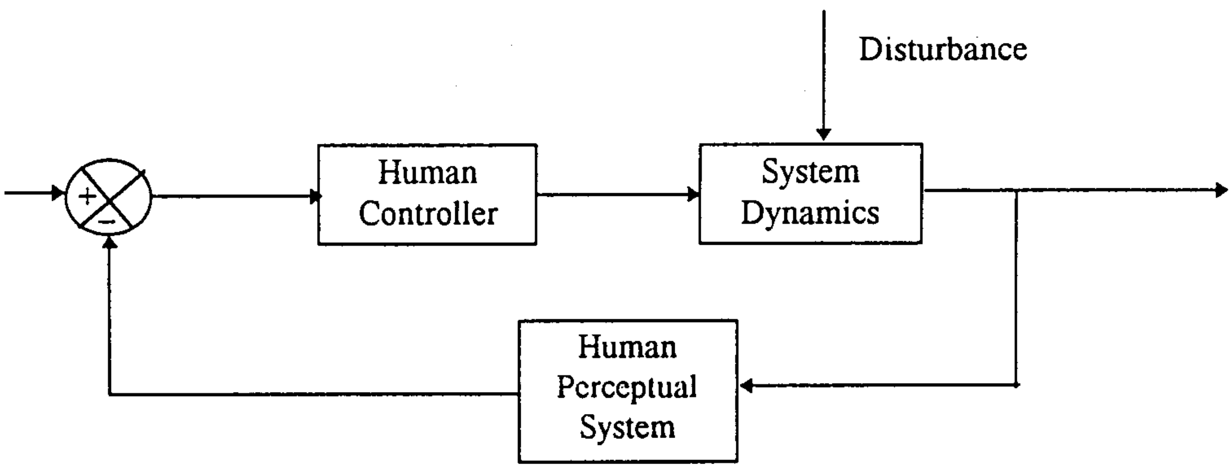

Figure 1.0. Man-machine System block Diagram.

All the means used to analyze classical control systems are applicable to man-machine systems. These systems can also be categorized as manual control systems. The term man-machine systems is, however, somewhat broader than manual control systems although the technologies are essentially the same. The man-machine system technically deals with all systems in which there is a human interface with a machine, which would include the discipline of ergonomics as well as arcade and personal computer games. These latter two applications while they are, in many cases, closed loop control systems they lack the de rigeur of most of the other applications

we will discuss.
This will not be a treatise on man-machine systems but a few issues will be illuminated at this point. If we consider the system in figure 1.0 the output can be characterized by several parameters: response time (measured several ways), accuracy, stability, remnant (the output power at non-input frequencies), and amplitude and phase in the frequency domain. These are not at all different from the criteria used to evaluate automatic control systems. In addition, however, human behavior must be considered as an evaluation criterion. This issue will be further developed both here and in subsequent lectures.

The problem in man-machine systems is to build a mathematical model of the human operator and use it in the system illustrated in figure 1.0. If the control system paradigm is pursued further in the context of continuous vs. discrete control systems, then it can be stated that the type of man-machine systems in which we are interested can be characterized as continuous. However, because the simulations are implemented in a digital computer, they become sampled data systems, by virtue of the sampling nature of the digital computer. Hence, the system has certain attributes of a digital control system.

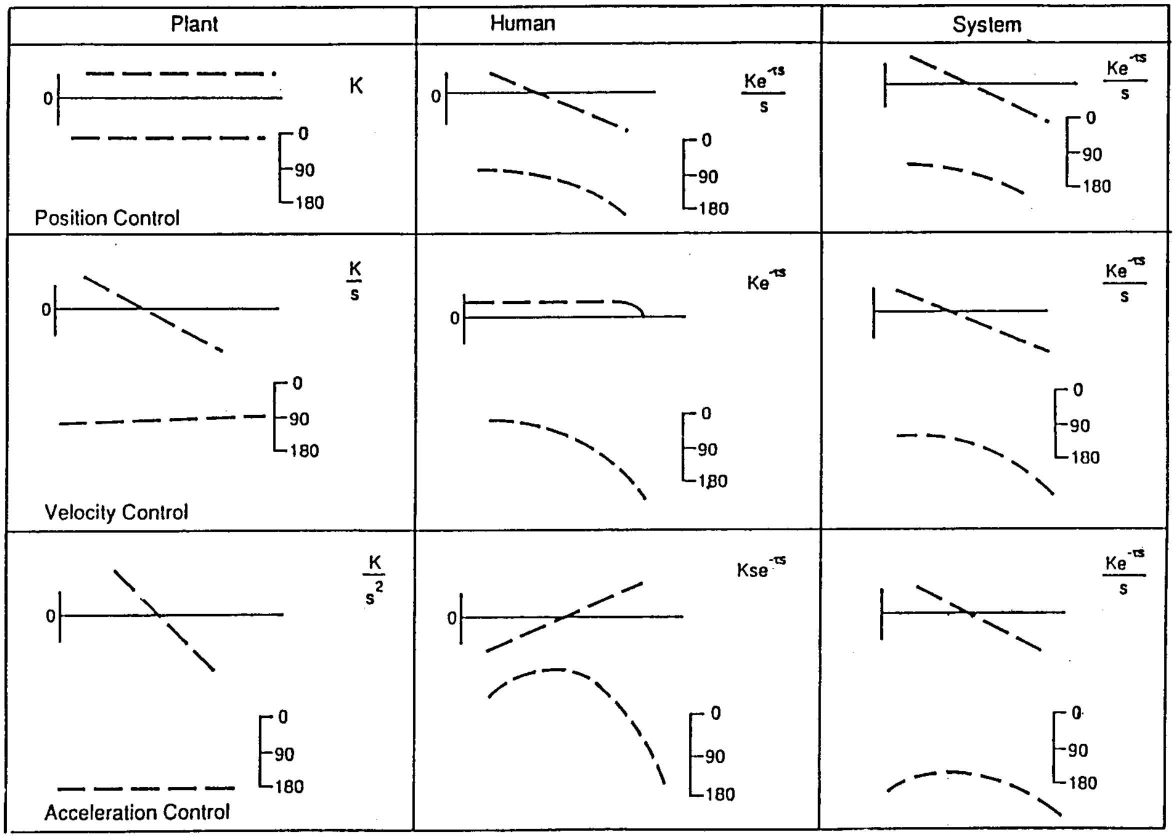

Figure 2.0 The basis of the crossover model as illustrated by three different plants.

The major issue here which discriminates the manual control system from the automatic control system is, as was stated previously, the control loop being closed through the human operator. How to accomplish the characterization of the human operator is the subject of concern here. It was originally assumed that when the human operator transfer function was determined, it was applicable to human performance over a wide range of plant dynamics. This assumption proved to be erroneous, as the plant dynamics changed, so did the describing function of the human operator. What was found to be invariant was the total forward loop transfer function. This invariant at the system level led to the development of the crossover model by Duane McRuer. Figure 2.0 (Flach) illustrates this invariance. Column 1 illustrates three simple plant dynamics. Column 2 illustrates the human operator describing function for each of the cases of plant dynamics. Column 3 illustrates the invariant forward loop, human plus plant, dynamics. Therefore, the crossover model predicts that, in the area of the crossover, the human plus the plant will approximate the transfer function shown in column 3. Furthermore, it has been shown that a human operator (pilot) will attempt to force the system to crossover between 3 and 6 rad/sec, with a phase margin of 25^o to 45^o.

Two other characterizations of the human operator are the structural isomorphic model, illustrated in figure 3.0 and the optimal control model (OCM), illustrated in figure 4.0

The structural isomorphic model attempts to model each of the elements of the human perceptual process in detail including an attempt at modeling the perceptual integration process. This element of the structural isomorphic model is indeed daunting. There have been and continues to be more sophisticated attempts at modeling this integration process, but they are beyond the scope of this course.

The optimal control model (OCM), which was developed by Sheldon Baron and David Kleinman, and is illustrated in figure 4.0, assumes that the human operator employs an internal (mental) model of the plant dynamics to estimate the current status of the system from delayed, noisy, observations of display position and velocity. The human responses to these states are based on optimal control law which; chooses response gains that minimize RMS error and control rate and filters them through neuromuscular dynamics contaminated by noise. Therefore, the OCM attempts to achieve minimum error with minimum effort. The OCM provides a better fit, over a wide range of frequencies, to human performance data, than does the crossover model. However, it requires a greater number of parameters and is, therefore, more complex. The OCM accounts for the remnant by assuming the presence of broadband noise injected by the human perceptual and motor processes.

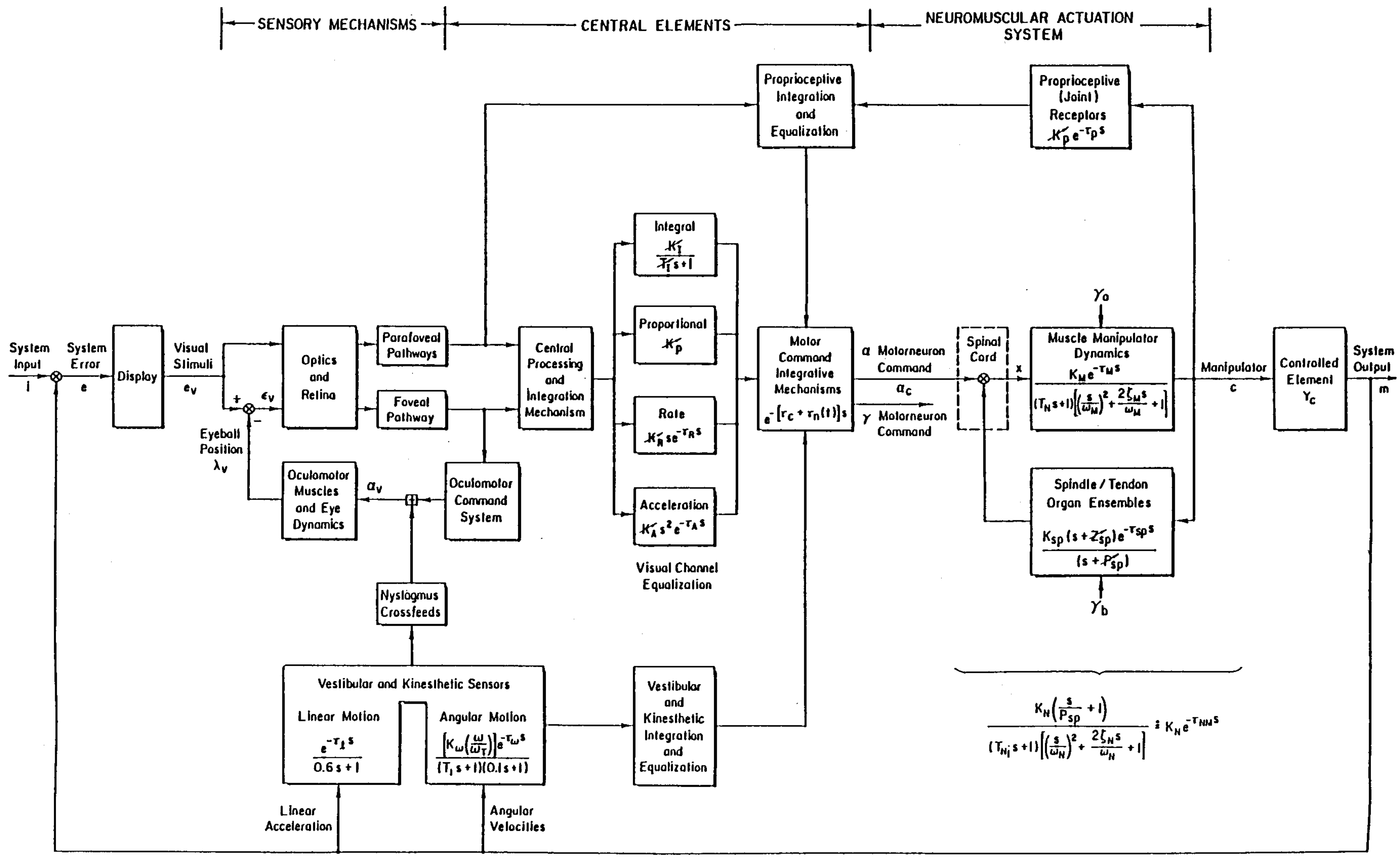

Figure 3.0. The Structural Isomorphic Model

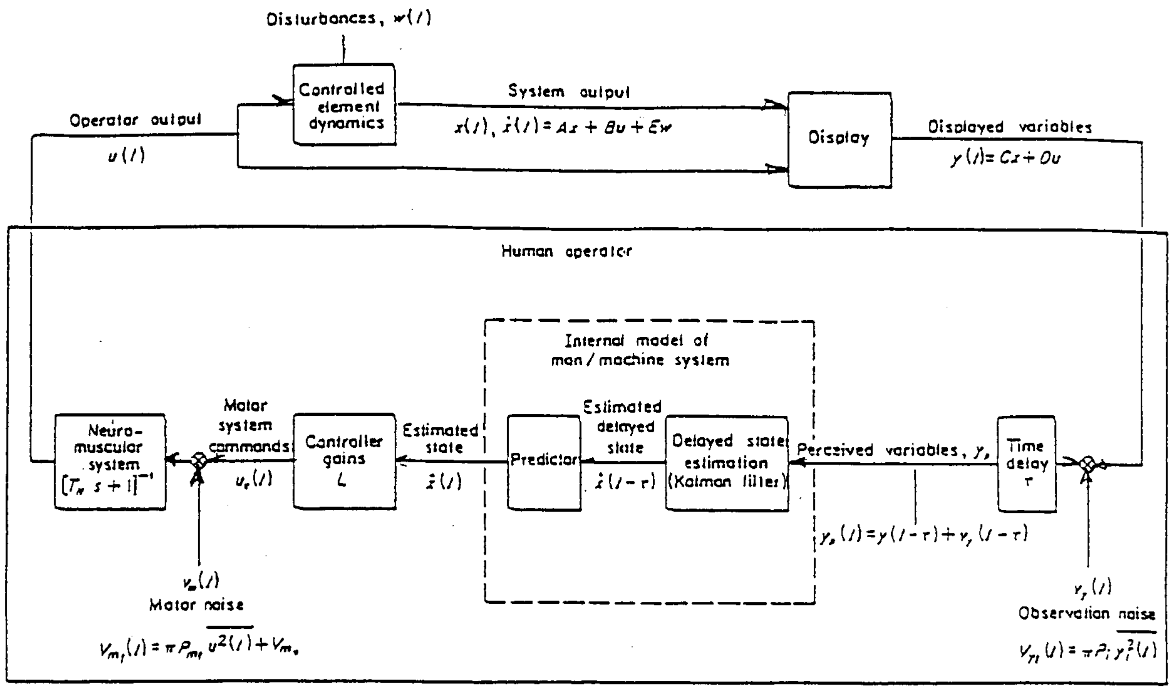

Figure 4.0. The Optimal Control Model (OCM)

A fourth approach to modeling the human operator is the so-called "intuitive model" presented by Thomas Sheridan and William Ferrell. This approach can include three properties: reaction time delay, a gain term and a neuromuscular lag term. This issue will be further developed both here and in subsequent lectures.

The reaction time delay is modeled as:

$$e^{-\tau s} \quad \textit{where} \;\; \tau \cong 0.15$$

The gain which is the product of the gains of the human plus the plant and is given as:

$$K = \left| Y_H \cdot Y_C \right| \quad \text{where} \quad 2 \le K \le 20$$

at low frequencies. The neuromuscular lag is modeled as a first order lag and has the form

$$\frac{1}{\tau_n s + 1} \qquad \textit{where } 0.1 \le \tau_n \le 0.20s$$

These yield the human operator transfer function,

$$Y_H = \frac{Ke^{-\tau s}}{1 + \tau_n s}$$

If this model is tested using human tracking data obtained by McRuer et al, employing a compensatory task with the transfer function Y_c = 1/s, Figure 5.0 can be used to illustrate the technique. The experimental data are plotted by the symbols representing different ω_i (cutoff frequency of the sum of sines forcing function used to drive the display). The longer dashed lines represent the gain and phase angle for Y_c = 1/s. Y_H would be given as the difference between the dashed curves of Y_c and the solid curves of the data. $Y_H = e^{-.15\,s}$ would not affect the gain but would have a $\phi = \omega\tau_r$. If a gain were added to the delay then the phase angle would not change but the gain would raised. The solid line represents a gain of 6. The phase angle solid curve is the $e^{-.15\,s}$ contribution plus the 1/s from the plant. Hence we have a resulting human transfer function of $Y_H\ Y_C$ shown below by the solid lines on the figure.

$$Y_H Y_C = \frac{6e^{-0.15s}}{s}$$

Notice that the gain crossover is at 4.5 rad/sec, the phase margin is 40^o and the gain margin is about 6dB.

This section is intended to give a brief overview of the technologies associated with analyzing the human-in-the control loop system.

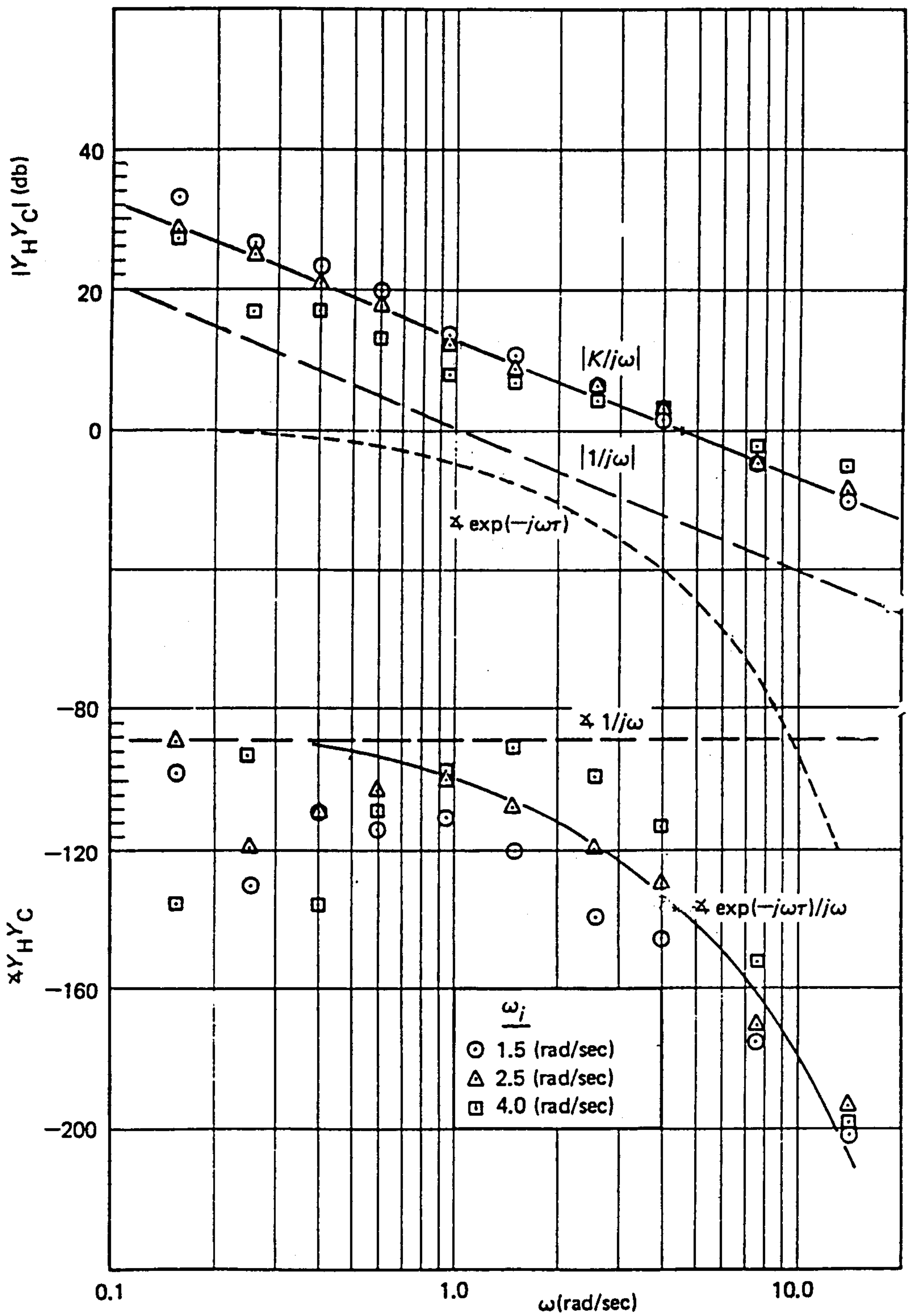

Figure 5.0 Compensatory Tracking Data from McRuer et al.

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