CONFIGURATIONAL AND SYSTEM REQUIREMENTS FOR CONTROL OF LARGE SPACE SYSTEMS

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INTRODUCTION

An overview on the subject of control of large space systems is offered in which anticipated modeling and control difficulties are discussed. Particular emphasis is given to issues that have received little attention in the current literature on the control of large space structures. The status of the control work that has been done to date on large space systems could be pictured as being at "the back-of-the-envelope" stage in contrast to the detailed analytical effort that will be required to ensure future operational systems controlability.

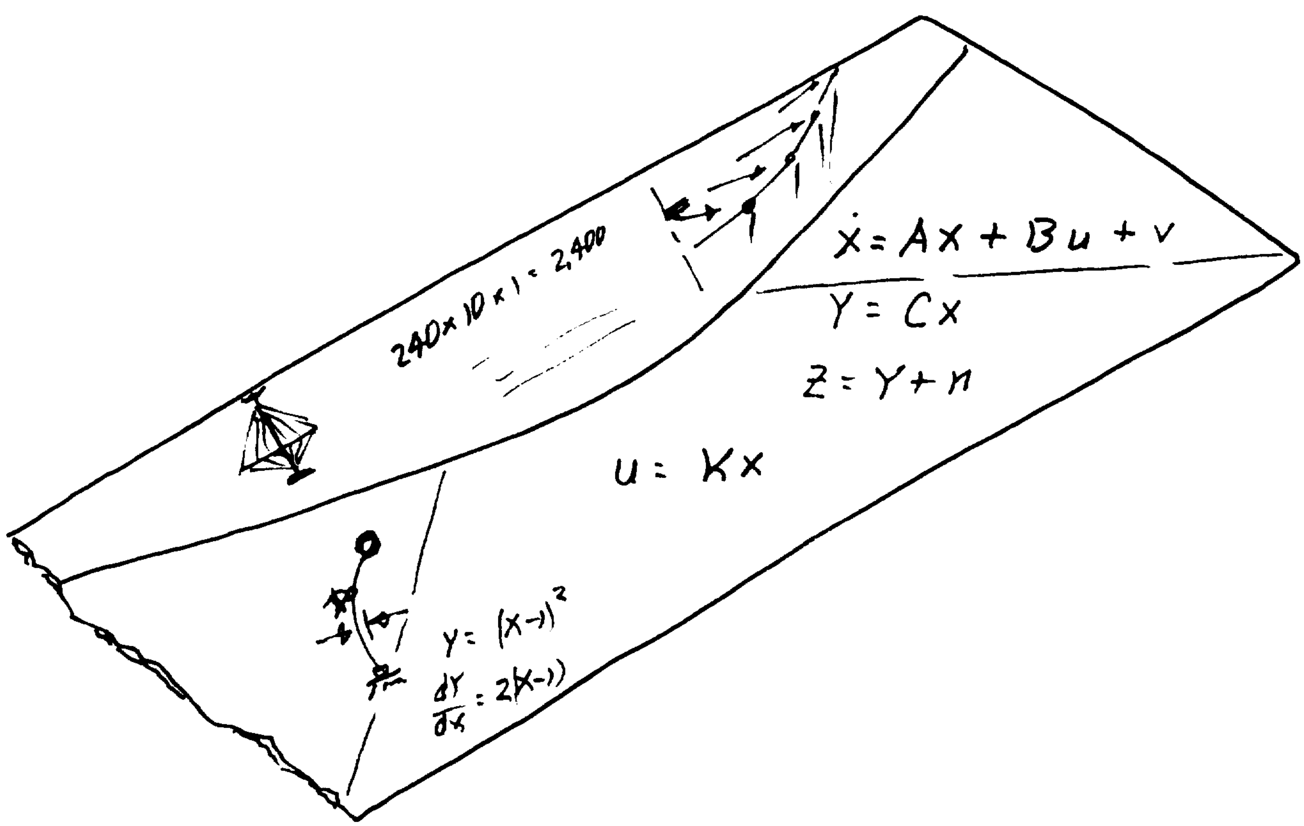


Figure 1

The discussion will be divided into two parts from the point of view of a specialist in systems identification. The first part of the discussion will deal with ground-based analysis of spaceflight data (1) to determine structural dynamics characteristics for the purpose of revising control laws, and (2) to trim the surface contour. The second part of the discussion is concerned with (1) systems identification for adaptive control and (2) auto-matic surface control.

SYSTEMS IDENTIFICATION FOR

LARGE SPACE SYSTEMS

GROUND-BASED ANALYSIS OF SPACEFLIGHT DATA TO:

- DETERMINE STRUCTURAL DYNAMICS
- REVISE CONTROL LAW
- TRIM SURFACE CONTOUR

ON-LINE AND ON BOARD FOR:

- ADAPTIVE CONTROL
- AUTOMATIC SURFACE CONTROL

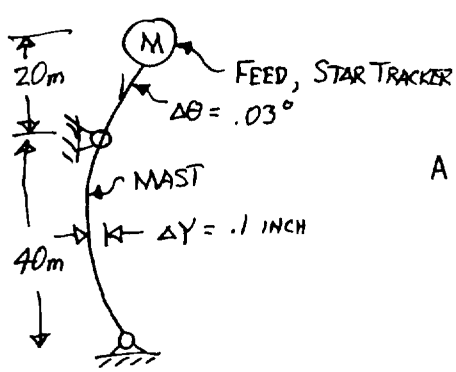
Figure 2

One might ask the questions "Why must structural dynamics be determined?" and "Why might pointing control involve structural dynamics?" The answers to these questions lie in the system requirements, structural dynamics characteristics, and the disturbance level. An example is offered in which an unacceptable 12-minutes settling time is required before a large flexible antenna meets its pointing requirement of .03° following a disturbance due to solar heating. For the example discussed, the effect of structural dynamics is crucial in the design of the pointing control system.

WHY MUST STRUCTURAL DYNAMICS BE DETERMINED?

WHY MIGHT "POINTING CONTROL" INVOLVE STRUCTURAL DYNAMICS?

A POINTING ACCURACY OF .03° REQUIRES THAT THE SUPPORTING MAST DEFLECT LESS THAN 1/10 OF AN INCH.



A STRUCTURAL FREQUENCY OF .1 HERTZ AND DAMPING RATIO OF .005 RESULTS IN A TIME TO HALF AMPLITUDE OF 221 SECONDS.

$$T_{1/2} = -\frac{\text{LOG } .5}{\zeta\omega_n} = 221 \text{ SECONDS}$$

SHOULD A SUDDEN DEFLECTION OF THE MAST OF 1 INCH OCCUR DUE TO SOLAR HEATING, THE POINTING ERROR WILL BE EXCESSIVE FOR 12 MINUTES.

Figure 3

In order to appreciate the importance of disturbances and noise, it is useful to observe that, for linear systems, its quasi-static error (no command input) is proportional to the amount of disturbance and noise. It behooves us then, to give these matters more attention. Sources of disturbances include solar (thermal and wind), on-board systems, and gravitational. Noise can come from sensors, actuators, and computers.

'LINEAR' SYSTEM PERFORMANCE IS PROPORTIONAL TO THE AMOUNT OF DISTURBANCE AND NOISE

DISTURBANCES
- SOLAR, THERMAL
- SOLAR, WIND
- ON-BOARD SYSTEMS
- GRAVITATIONAL

NOISE
- SENSOR
- ACTUATOR
- COMPUTATIONAL
- QUANTIZATION

Figure 4

Because of the relative ease with which linear systems can be analyzed, nonlinearities are often neglected. Unfortunately, the nonlinearities can greatly affect system response, particularly at very large and very small amplitudes of motion. Nonlinear behavior generally comes from sensors, actuators and inertial coupling. It can be expected that system nonlinearities will result in limit cycles in pointing, in orbit maintenance, and probably at some structural modal frequencies.

SENSOR AND ACTUATOR NONLINEARITIES WILL RESULT IN LIMIT CYCLES IN POINTING, ORBIT MAINTENANCE, AND PROBABLY AT SOME STRUCTURAL MODAL FREQUENCIES

NONLINEARITIES

- ACTUATOR AND SENSOR SATURATION
- ACTUATOR HYSTERESIS
- SENSOR DEADBAND
- INTENTIONAL CONTROL CHARACTERISTICS

Figure 5

To close the first part of the discussion, we consider the computational aspects of ground-based analysis of spaceflight data. Transient analysis techniques will be required, either in the frequency or time domains. Attempts to determine the steady-state response to a sine-wave input, for example, are easily frustrated by lightly damped modes with little frequency separation. The instrumentation requirements are outlined and seen to be ordinary. Although the ground-based computer requirements are expected to be quite modest, the analysis techniques should first be tested using ground test data.

THE COMPUTATIONAL TASKS OF GROUND-BASED ANALYSIS OF SPACEFLIGHT DATA ARE ONLY MODERATELY DIFFICULT

STRUCTURAL DYNAMICS MODELING

- TRANSIENT ANALYSIS TO BE USED
- NO SPECIAL INSTRUMENTATION IS REQUIRED
- SPECIAL CONTROL INPUTS REQUIRED
- PERHAPS 10 MODES CAN BE MODELED
- NEED SAMPLE RATE OF 5 TO 10/SECOND
- NEED DATA LENGTH OF ABOUT 30 SECONDS
- GROUND-BASED COMPUTER REQUIREMENTS ARE INSIGNIFICANT
- SHOULD TEST ANALYSIS TECHNIQUE WITH GROUND TEST DATA

Figure 6

Turning to the problem of adjusting the surface contour of a large space system, we can expect that a static analysis will be sufficient, though extensive special instrumentation will be required. Repeated measurements serve to improve the accuracy in determining the surface contour and can detect surface motion. Analysis procedures should be tested using ground test data.

SURFACE CONTOUR ADJUSTMENT

- STATIC ANALYSIS TO BE USED
- EXTENSIVE INSTRUMENTATION REQUIRED
- CONTROL INPUTS, DISTURBANCES NEED TO BE MINIMIZED
- PERHAPS 240 SURFACE MEASUREMENT LOCATIONS
- PERHAPS 4 SETS WILL BE NEEDED
- MUST INVERT 240 × 240 MATRIX
- SHOULD TEST ANALYSIS TECHNIQUE WITH GROUND TEST DATA

Figure 7

Examination of the distribution of modal frequencies reveals the difficulty in controlling large space systems at frequencies exceeding the first structural mode. A control bandwidth reaching a frequency ratio of 3.0 might become a typical limit. Difficulties arise in modeling, also the modes become packed. The particular dynamic characteristics must be examined, however, to make a meaningful assessment.

A SYSTEM HAVING A LARGE NUMBER OF CLOSELY SPACED MODES IS DIFFICULT TO MODEL

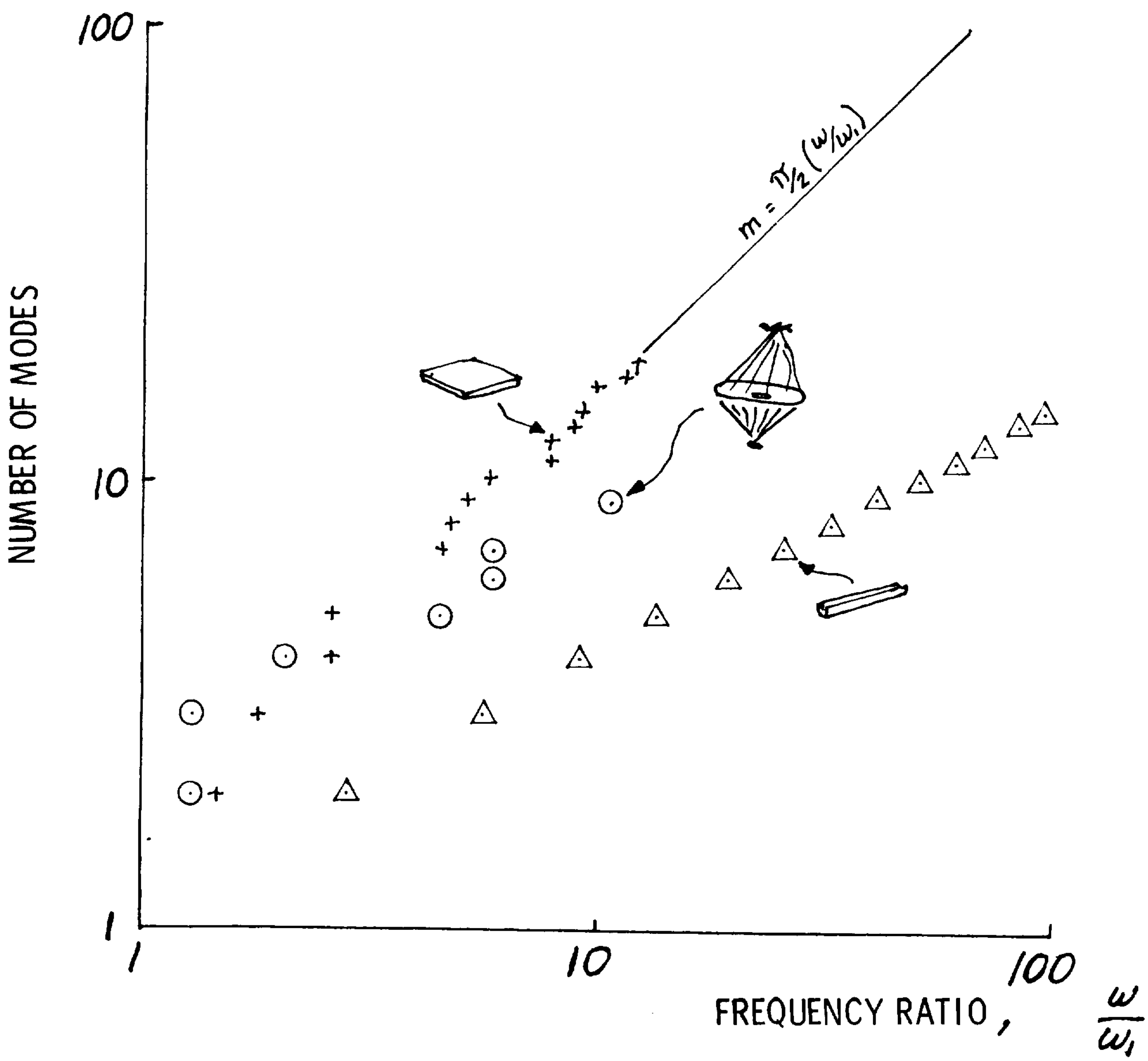


Figure 8

It should be noted that the limits to the effectiveness of control systems depends on the degree to which the control law can be adjusted. The bandwidth of a fixed control law will probably be limited to about the first structural mode of a large space system. If adjustment of the control law is possible after analyzing spaceflight data, then it should be possible to increase the control bandwidth, perhaps by a factor of two. Adaptive control would allow even tighter control by continually adjusting control in response changing conditions.

"THERE ARE LIMITS TO THE EFFECTIVENESS OF CONTROL SYSTEMS"

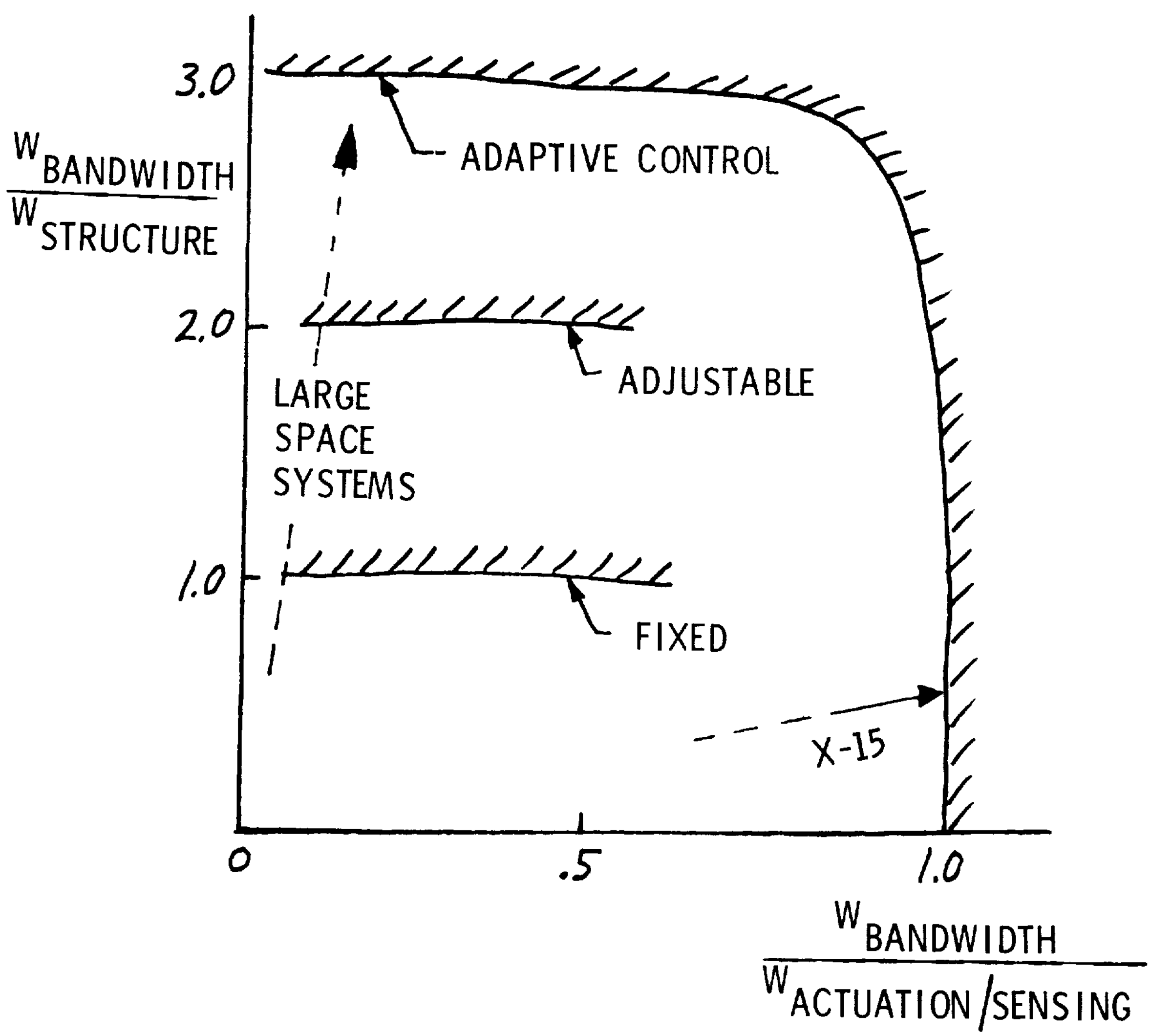


Figure 9

If the size of large space systems becomes bounded by control limitations, stiffer configurations will have an advantage. Their relatively higher structural frequencies enable control bandwidth requirements to be met for larger sized configurations. The hoop/column antenna, for example, is about four times as stiff as the offset wrap-rib configuration of the same diameter. For multi-frequency applications, this advantage narrows to a factor of two because of the lack of blocking for the offset configuration.

"IF THE SIZE OF LARGE SPACE SYSTEMS BECOMES BOUNDED BY CONTROL LIMITATIONS, STIFFER CONFIGURATIONS WILL HAVE AN ADVANTAGE"

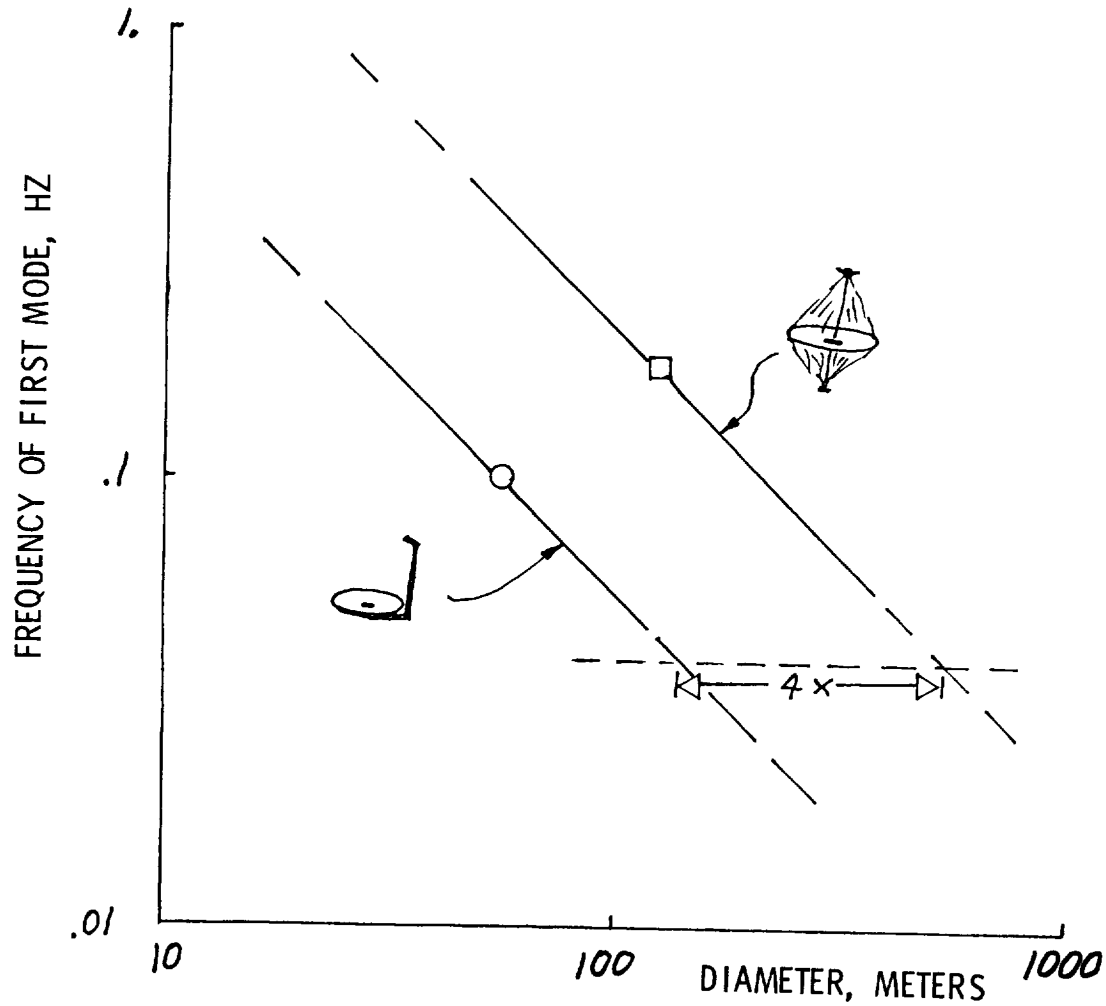


Figure 10

On-line systems identification for adaptive control of large space systems requires additional development, although simple forms of adaptive control would require less work. Practicalities are expected to limit the number of structural modes that can be modeled, on-line, to about four. Intentional disturbances will be required to produce response signals which can be separated from noise and unmodeled disturbances. The computational load is not insignificant, but lies within a practical range.

ON-LINE SYSTEMS IDENTIFICATION FOR ADAPTIVE CONTROL REQUIRES ADDITIONAL DEVELOPMENT

- SIMPLE FORMS OF ADAPTIVE CONTROL REQUIRE LESS DEVELOPMENT
- MAXIMUM LIKELIHOOD ESTIMATION WOULD BE USED
- NO SPECIAL INSTRUMENTATION IS REQUIRED
- SOMEWHAT OBTRUSIVE CONTROL INPUTS WOULD BE REQUIRED
- PERHAPS 4 STRUCTURAL MODES CAN BE MODELED, ON-LINE
- NEED SAMPLE RATE OF 10/SECOND
- UPDATE AFTER 30 SECONDS MIGHT BE POSSIBLE
- REQUIRES COMPUTATIONAL RATE ON THE ORDER OF 2.2 M OPS

SENSITIVITY EQUATIONS — $MX^2 * NC * N = 14^2 \cdot 100 \cdot 300$

INFORMATION MATRIX — $MZ^2 * NC^2 * N = 20 \cdot 100^2 \cdot 300$

INVERSE — $NC^2/3 = 100^3/3$

Figure 11

Automatic surface control of a large space structure is straightforward but is dependent on the accuracy and rapidity of surface measurements. The larger number of sensors and actuators involved in surface contour control will require fault management. The need for active surface control has not yet been established, but will depend on surface accuracy specifications, structural damping, and disturbance levels. Surface control at a particular point would need surface deflection information over a limited region.

AUTOMATIC SURFACE CONTROL IS STRAIGHTFORWARD

- BANDPASS OF SURFACE CONTROL IS PACED BY RATE OF MEASURING SURFACE DEFLECTION
- MUST ACCOUNT FOR FAILED SENSORS AND ACTUATORS
- PERHAPS 240 SURFACE MEASUREMENT LOCATIONS
- SIMPLE, CONSTANT GAIN, FEEDBACK CONTROL ADEQUATE
- COMPUTATIONAL REQUIREMENTS ARE MODEST ~ 50K OPS

  CONTROL ⟶ $9 \cdot 240 \cdot 1 = 2160$

  FILTER ⟶ $20 \cdot 240 \cdot 10 = 48,000$

  REDUNDANCY ⟶ ?
- NEED FOR AUTOMATIC SURFACE CONTROL DEPENDS ON:

  RF REQUIREMENTS

  SURFACE RESPONSE TO DISTURBANCES, CONTROL,

  DEGREE OF STRUCTURAL DAMPING

$$u_{i,j} = \sum_{l=i-1}^{i+1} \sum_{m=j-1}^{j+1} k_{l,m} x_{l,m}$$

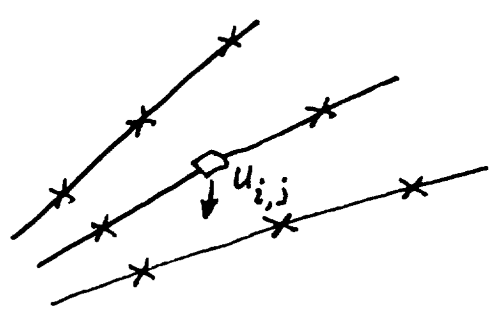


Figure 12

CONCLUDING REMARKS

- STRUCTURAL DYNAMICS MUST BE CONSIDERED IN DESIGNING EVEN POINTING CONTROL FOR LARGE SPACE SYSTEMS.
- DISTURBANCES, NOISE, AND NONLINEARITIES DRIVE THE CONTROL SYSTEM DESIGN.
- ADJUSTMENTS OF CONTROL GAINS AND SURFACE CONTOUR USING GROUND-BASED ANALYSIS ARE ONLY MODERATELY DIFFICULT.
- ADAPTIVE CONTROL PROMISES IMPROVED CONTROL BUT REQUIRES ADDITIONAL DEVELOPMENT.
- AUTOMATIC SURFACE CONTROL IS STRAIGHTFORWARD.
- CONTROL AND ANALYSIS TECHNIQUES NEED TO BE TESTED USING GROUND AND TEST-FLIGHT DATA.