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MARK III TPA STABILITY ANALYSIS

A Presentation to SNPO-C

NERVA PROGRAM

CONTRACT SNP-1

19 MARCH 1964

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the Mark III Pumping System	
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Applied to a Mark III Mod 4
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III.	REVIEW OF LASL CONCLUSIONS	J. J. Carroll
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STABILITY ANALYSIS OF MARK III CENTRIFUGAL PUMPING SYSTEM

On 4 March 1964, Los Alamos Scientific Laboratory presented a preliminary stability analysis of the Mark III centrifugal pumping system at the SNPO-C coordination meeting. The analysis was based on a linearization of equations derived in LASL Memorandum N-4-2263. From this linearized investigation and the application of a certain set of operating conditions, it was concluded by LASL that a pump with positive slope characteristics would be unstable.

Aerojet has been engaged in an intensive investigation of the stability of the Mark III pump. Aerojet's findings do not agree with those presented by LASL at the meeting of 4 March. Aerojet therefore examined the LASL report to determine the prime differences between the Aerojet and LASL model concepts.

Aerojet, in its dynamic analysis of the pump, has employed a simulation of the engine as a pump load. This type of load differed significantly with the simple load employed by LASL. However, it was noted that LASL included a fluid compressibility term in the pump discharge which was not contained in the Aerojet model. This factor was therefore added to the dynamic simulation to determine its effects on stability.

With fluid compressibility included in the model, the pump equations were programmed to solve along the parabolic approximation of

$$\frac{\Delta P}{N^2} \text{ vs } \frac{Q}{N}$$

for a constant

$$\frac{\Delta P}{N^2} = .5 \times 10^{-6} \frac{\text{ft}}{\text{RPM}^2}$$

The simulation was then adjusted to provide dynamic solutions at the operating point selected by LASL. While operating with closed control loops, the system was found to be stable to step disturbances. Responses of the same system with pump speed fixed were also found to be stable. The pump speed and temperatures entering the pump calculations were then fixed. Again, the system showed a stable response to a step disturbance. Since the system was stable at this operating point, the pump load was adjusted to develop a Q/N of 0.250 at the same temperature as previously used. Again, the system was found to be stable.

To further develop the investigation, system responses were investigated at the various points on the operating map shown in Figure 1. A systematic approach was employed as shown by the directing arrows from one point to another.

MARK III TPA STABILITY ANALYSIS

STEADY STATE OPERATING MAP

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FIGURE 1

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ANALYSIS OF LASL EQUATIONS OF THE MARK III PUMPING SYSTEM

A dynamic simulation of the LASL equations was made. The unstable results were anticipated and proved out by the simulation. This was evident with the positive feedback term to the pump equation being larger than the two negative feedback terms in the loop. Figure 2 shows the simulation of this unstable condition.

MARK III TPA STABILITY ANALYSIS

RESPONSE OF NON-LINEAR SIMULATOR OF
LASL STABILITY INVESTIGATION

FIGURE 2

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The load on the LASL equations was then changed to approximate that used by Aerojet in the TPA test. Results of this simulation are shown in Figure 3. It can be seen that while lightly damped, the system is stable.

MARK III TPA STABILITY ANALYSIS

RESPONSE OF NON-LINEAR SIMULATOR USING
LASL EQUATIONS APPLIED TO
AEROJET TPA TEST SETUP

FIGURE 3

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The load on the LASL equations was further changed to approximate the engine. As shown by Figure 4, the system was found to be completely stable.

MARK III TPA STABILITY ANALYSIS

LASL EQUATIONS APPLIED TO AN
EQUIVALENT ENGINE FLOW IMPEDANCE

FIGURE 4

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Figure 5 illustrates the response of this system to a step disturbance.

MARK III TPA STABILITY ANALYSIS

RESPONSE OF NON-LINEAR SIMULATOR USING
LASL EQUATIONS APPLIED TO AN
EQUIVALENT ENGINE FLOW IMPEDANCE
WITH EXTERNAL STEP DISTURBANCE

FIGURE 5

ANALYSIS OF LASL EQUATIONS AS APPLIED TO A MARK III MOD 4 PUMPING SYSTEM

It was desired to consider the response of a pumping system utilizing a pump with negative slope characteristics and the LASL equations. Therefore, preliminary data from Case 3 of a Mark III Mod 4 pump was reduced to the parabolic form used in the simulation. Figure 6 shows that the system was stable to step disturbances.

MARK III TPA STABILITY ANALYSIS

RESPONSE OF NON-LINEAR SIMULATOR OF
LASL STABILITY INVESTIGATION
WITH MARK III MOD. 4 CASE 3 PUMP

$$\frac{H_{sv}}{N^2} = .5 \times 10^{-6} \frac{\text{ft}}{\text{RPM}^2}$$

FIGURE 6

REVIEW OF LASL CONCLUSIONS

During the stability analysis presented by LASL to the SNPO-C coordination meeting, the main conclusions were, that for the system and boundary conditions investigated, a pump with positive slope characteristics would be unstable. Figures 7, 8, and 9 list some of the implications of the system considered by LASL in their analysis. A primary conclusion is that the stability criteria for the fluid system described by LASL indicates that the pump flow rate is divergent at the operating point considered in the analysis. It was further concluded that if the proper values of damping are added to the system, it would be stable.

MARK III TPA STABILITY ANALYSIS

LIMITATIONS OF LINEARIZED SYSTEM ANALYSIS PRESENTED AT SNPO-C 3-4-64

- (a) Speed was not an independent variable as it appeared in only one equation and no specific solution for any one variable could be presented explicitly in terms of speed alone.
- (b) System had four equations and five unknowns; therefore solution in terms of Routh's criteria could not be presented. Unknowns were: δN , $\delta \dot{w}_p$, $\delta \dot{w}_3$, δP_{pe} , δP_{ri} .
- (c) It must therefore be implied that speed was a constant in this analysis.
- (d) If δN was made a dependent variable then the system would have a zero in the right-hand half plane which would coincide with a physically unrealizable network in terms of electronic network synthesis.
- (e) Compressibility constant, K_{t2} was for liquid hydrogen at 40°R and did not consider deflection of pipe diameter.
- (f) Pump discharge equivalent line length of 10 feet and frictional loss of 20 psi are not too realistic for any system so far designed for NP-1.

FIGURE 7

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MARK III TPA STABILITY ANALYSIS

LIMITATIONS OF PHYSICAL MODEL AS DESCRIBED IN N-4-2263

- (a) Terminating Impedance Concept not representative of a reactor type load; i.e., $\Delta P \propto \dot{w}^2$ should be $\Delta P \propto \dot{w}$ if used to analyze a pump-reactor system.
- (b) Turbopump speed was not related to a torque balance; i.e., no equation was presented that identified the inertial behavior of the pump. Therefore, speed could not be an independent variable.
- (c) A constant fluid density was considered throughout the system.
- (d) Equations that describe the momentum and continuity conditions of the fluid in transit were considered as lumped parameter or point functions. The system behavior that varies continuously in both space and time was examined at only one point and the distributed physical effects were combined (lumped) to operate at this point.

FIGURE 8

MARK III TPA STABILITY ANALYSIS

COMPARISON OF MOMENTUM AND CONTINUITY EQUATIONS AS DESCRIBED IN N-4-2263

LEGEND: Let (a) = Physical equations and (b) = N-4-2263 equations

MOMENTUM OF FLUID SYSTEM

$$(a) \quad -\frac{1}{\rho} \frac{\partial P}{\partial X} = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial X}$$

$$(b) \quad P_{pe} - P_{r1} = \frac{L_2}{A_2 g} \frac{d\dot{w}_p}{dt} + R_2 \dot{w}_p^2$$

$$\text{where } \frac{\partial P}{\partial X} \triangleq P_{pe} - P_{r1}$$

$$\rho \frac{\partial u}{\partial t} = \frac{L_2}{A_2 g} \frac{d\dot{w}_p}{dt}$$

$$\rho u \frac{\partial u}{\partial X} = R_2 \dot{w}_p^2$$

CONTINUITY OF FLUID SYSTEM

$$(a) \quad \frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial X} = 0 \quad \text{If } c^2 = \frac{\gamma P}{\rho}$$

$$\text{then } (a) = \frac{\partial P}{\partial t} = \frac{c^2}{\gamma} \frac{\partial \rho u}{\partial X}$$

$$(b) = \frac{dP_{r1}}{dt} = \frac{K_{t2}}{V_2} (\dot{w}_p - \dot{w}_3)$$

$$\text{where } \frac{\partial P}{\partial t} = \frac{dP_{r1}}{dt}$$

$$\frac{c^2}{\gamma} = \frac{K_{t2}}{V_2}$$

$$\frac{\partial \rho u}{\partial X} = (\dot{w}_p - \dot{w}_3)$$

FIGURE 9

A mechanical or electrical model of the linearized LASL system can be constructed as illustrated in Figure 10. The system will be stable if the sum of the equivalent electrical resistances or mechanical damping terms are positive at the point under investigation. If the sum of these terms are negative, then the system is physically unrealizable (or unstable) in terms of impedances related to a constant speed device. The electrical equivalent circuit considers δN as a current generator of normalized value initially dependent on its own load resistance.

MARK III TPA STABILITY ANALYSIS

LINEARIZED PUMP STABILITY EQUATIONS (N-4-2263)

$$(a) \quad \delta P_{PE} = (2N_o K_1 + K_2 W_{po}) \delta N + (2K_3 W_{po} + K_2 N_o) \delta \dot{W}_p$$

$$(b) \quad \delta P_{PE} = \delta P_{RI} + (2R_o \dot{W}_{po} + L_2 s) \delta \dot{W}_p$$

$$(c) \quad \delta P_{RI} = \frac{1}{s} \left(\frac{K_{T2}}{V_2} \right) (\delta \dot{W}_p - \delta \dot{W}_3)$$

$$(d) \quad \delta P_{RI} = (2R_3 \dot{W}_{30}) \delta \dot{W}_3$$

EQUIVALENT ELECTRICAL MODEL

EQUIVALENT MECHANICAL MODEL

FIGURE 10

CONCLUSIONS

Aerojet is continuing its investigation of the Mark III stability. At present a detailed linear analysis of the TPA and feed system is being prepared. This analysis will be presented at a later date upon completion.