BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B70 05026

SUBJECT: A Theory of S-II POGO
Case 320

DATE: May 14, 1970

FROM: J. J. O'Connor

ABSTRACT

A theory has been derived from study of various flight data which qualitatively describes the S-II POGO phenomenon of SA-504, SA-507 and SA-508. It is stated as follows. The cavitation caused by pump vibration is non-linear; it adds compliance to the LOX line; and it increases the phase lag around the loop. In an unstable system which is diverging, this increased phase lag across the line must be compensated by decreased phase lag across the structure to maintain zero loop phase. This explains the mysterious feature of S-II POGO in which we get decreasing frequency with increasing amplitude of oscillation at the onset of the instability.

This cavitation non-linearity can lead to a steady amplitude of oscillation which tracks the structural modes. They are slowly varying in amplitude and frequency during the early portions of stage operation (SA-507).

At certain levels of oscillation, the cavitation non-linearity can lead to double-valued response curves and produce an amplitude jump phenomenon, that is, a sudden increase of pump "gain." This accelerates the decreasing-frequency, increasing-amplitude transient and results in a large amplitude of steady-state oscillation (SA-504).

The SA-508 events have the same features as SA-507 and SA-504 until a new (and still unexplained) amplitude-triggered increase of "gain" caused the violent divergence of oscillation amplitude. This "gain" increase might be due to "hard" cavitation within the vibrating pump or it might be due to the non-linear stiffness of the center engine beam when the amplitude of oscillation imposes loads near the yield and/or ultimate strength of the beam.

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MEMORANDUM FOR FILE

INTRODUCTION

Study of the S-II contour spectrograms indicates that the SA-508 POGO had the same mysterious behavior as SA-504: there is a rapid decrease of frequency at the same time as the rapid increase of oscillation amplitude. The original SA-504 intensity spectrograms indicated that this might have been due to the intersection of two structural modes. We made several attempts to generate such a structural model but the modes would always repel each other rather than "intersect." We did find that additional phase shift in the engine transfer function would cause the frequency of minimum stability (the zero phase gain crossing) to fall below that of the structures resonance frequency. While this would reproduce the frequency reversal observed in flight, we could find very little justification at that time for such an arbitrary manipulation of engine phase shift.

A new insight was gained for SA-504 from the contour spectrograms, as seen on Attachment I taken from Reference 1. There seems to be a single structural mode passing through the points of 220 sec, 11 Hz; 470 sec, 16.5 Hz; 540 sec, 19 Hz; The POGO signal starts on this mode at 510 seconds, falls below it as the amplitude rapidly increases, and then slowly returns to the modal frequency as the amplitude gradually decreases. This characteristic was described as mysterious and unexplained in Reference 1.

Thanks to the stimulating presentations and private conversations at the MSFC POGO Working Group Meeting on April 23, 1970, R. V. Sperry, A. T. Ackerman and the author pieced together a theory which we think describes the SA-504, SA-507 and SA-508 experiences. It further describes the limiting mechanism that Dr. Mueller was looking for a year ago. But first let us make a few observations that will be useful during the description of the theory.

FIRST OBSERVATION

The first observation is that a closed-loop system which is oscillating at a steady-state amplitude will not (necessarily) oscillate at a frequency of maximum (open-loop) gain but will oscillate at the frequency which gives zero

(or multiples of 360 degrees) phase shift around the loop. That is, the signal must reproduce itself exactly at any point in the loop. Once such a frequency is established, the amplitude of the oscillation is determined by the non-linear element which is necessary to have a steady-state oscillation amplitude. The amplitude is such that it will produce the phase shift in the non-linear device which is necessary for zero loop phase.

This first observation is very important and is not often considered in the usual stability analyses, which generally are more concerned about the amplitude of the loop gain. Therefore, let us go through it again. If a system is slightly stable and the gain is increased, it can cause the system to become unstable. But once the system is unstable, the gain is unimportant. In a sense there is infinite gain available since the signal can more than reproduce itself. Therefore, the gain merely determines the rate of divergence. But the signal must reproduce itself with exact timing, that is, phase. If it does not, there is a frequency-pulling effect, accompanied by an amplitude change, and indeed this is what happens during a transient build-up period. The steady state condition is then accomplished when the phase requirements are satisfied with whatever amplitude is necessary.

Since the signal must reproduce itself, the non-linear system with a steady-state amplitude of oscillation has, in some sense, unity gain. Both the phase and the gain conditions can be examined by use of the Nyquist plot. Of course, a Nyquist plot strictly applies only to a linear system, but let us visualize it as describing the behavior of the fundamental component of the non-linear oscillation waveform.

If the locus on the Nyquist plot encloses the (1,0) point, the system is unstable and a diverging signal will start. The non-linear element will cause a phase shift of this diverging signal and this will tend to rotate the locus on the Nyquist plot. If this moves the locus further away from the (1,0) point, the signal will further diverge; there will be more phase shift, followed by more rotation of the locus. If there is to be a steady-state amplitude of oscillation, the locus will eventually move back toward the (1,0) point. When it passes through that point, we have an amplitude of oscillation which gives zero loop phase and unity gain.

If this is to be a "stable" operating point, the system must return to it after a transient perturbation. That is, a sudden decrease of oscillation amplitude (from any cause whatsoever) will cause the locus to move to the right of the (1,0) point. This will cause the system to diverge from that point, increase the amplitude of oscillation, drive the locus

back to the (1,0) point, and thereby re-establish the unperturbated amplitude of oscillation. Similarly, a sudden increase of oscillation amplitude will move the locus to the left of the (1,0) point, tend to stabilize the system, and cause a decay of oscillation amplitude back to the unperturbated value, returning the locus to the (1,0) point.

SECOND OBSERVATION

The second observation deals with a characteristic of the S-II structure as gleaned from the structures models. There are several LOX tank modes all of which increase in frequency as the propellants are consumed. As these modes pass through the 16 Hz region, they couple with the center engine truss and present high gains to the center engine gimbal point. That is, there is a sequence of high gain modes in the 16 Hz region as the several LOX tank modes pass this band. This feature has been used to explain the SA-507 POGO "footballs" which are a series of diverging and converging oscillations. The limited amplitudes of these "footballs" led to the belief that they were the noise-excited response of a stable system or the transient response of an unstable but time-varying system. Neither explanation is necessary in light of this new theory.

THIRD OBSERVATION

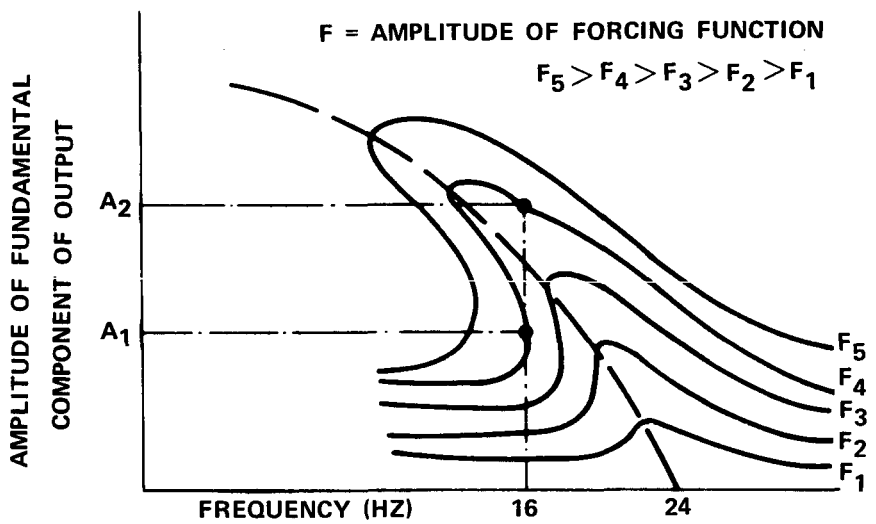
The third observation deals with the LOX suction line and the pump. Even under steady-state conditions (that is, without any oscillations) there is cavitation at the inlet of the pump. This cavitation reduces the resonance of the line from well above 100 Hz to the 21-24 Hz region.

Further, all measurements of pump-engine gain have made by considering the slopes of steady-state characteristics or by pulsing the LOX flow with an overboard bleed. The cavitation during inflight POGO, however, is caused by the physical vibration of the pump interacting with the column of LOX in the line supported by the pump. The physical motion of the pump blades in the LOX and the changes of the inducer angle of attack due to the relative motion can cause changes in the cavitation, line tuning and pump gain. These changes have not been investigated experimentally.

Also, the unstream turbulence, inducer backflow and wall attachment effects make the inlet pressure transducer measurement of questionable value in determining pump gain. In fact the whole concept of a pressure gain across the pump under these conditions is meaningless. What is really needed is the gain as the ratio of chamber pressure (or pump discharge flow) per g of line-pump oscillatory acceleration over the frequency and NPSH regions of interest.

FOURTH OBSERVATION

The comments under the preceeding observation indicate that the compliance due to pump cavitation is an instantaneous function of the pump acceleration. That is, this compliance is the non-linear mechanism which causes the phase shift across the line-pump to be a function of signal amplitude. As a non-linear compliance, one is tempted to think of a non-linear spring in a mechanical system. This leads to a non-linear differential equation, the solution of which requires some a prior insight (Reference 2). If the spring is "soft" there is a reduction of the resonant frequency for increasing signal amplitude, as shown in this sketch:



Note from the sketch that if the line is resonant (for zero amplitude forcing function) at 24 Hz and the "structural" oscillation is near 16 Hz and slowly increasing in frequency, there is a specific forcing function amplitude F_4 which will cause the output to suddenly jump from A_1 to A_2.

Further, if the "spring constant" function is non-odd $[-f(-x) \neq f(x)]$ the output will contain a dc bias (even with a sinusoidal forcing function) and this dc amplitude will suddenly change when the fundamental component of the output changes (Reference 3). The line-pump "spring constant" function is non-odd because we are operating about an offset due to the steady state NPSH.

It is interesting to note that an increased "spring constant" with increased NPSH connotes a "hard" spring. However, the dc bias term moves the operating point below the

non-oscillation NPSH value as the ac amplitude build up and thereby derives a "soft" spring effect.

THE THEORY

In this description of the theory we will use the chart Rocketdyne presented at the POGO Working Group Meeting (Attachment II) since it is so close to describing the phenomenon. Actually it was used to present the flight events.

Initial Conditions

Consider the system just before it goes unstable. There might be a 16 Hz signal visible in the measurements due to the noise excitation of the stable system which acts as a filter. Let this condition be designated as point 1 on Attachment II. (In the structure block, point 1 is shown to the right of the structural resonance; this is not important to the theory as point 1 could be near the structural resonance or even a little to the left of it.) The location of point 1 on the open-loop gain locus of the Nyquist plot is probably near the (1,0) point as this would be the least damped filter response of the stable system.

Onset of Instability

Consider now increases in structures gain as mentioned under the second observation. When the in-phase loop gain reaches unity, the system becomes unstable. The initial frequency of oscillation is at point 1 if the loop phase is exactly zero; that is, if the phase lag through the structure matches that of the line such that the loop phase is a multiple of 360 degrees. However, the instability will cause the oscillation amplitude to increase. This will increase the line excitation (pump vibration). Now we must consider the non-linear effects of inlet cavitation due to pump vibration. This non-linearity causes the effective cavitation to increase with oscillation amplitude. This increased cavitation (incidentally) decreases the line resonance but more importantly increases the phase lag across the line. To balance this increased lag, the frequency of oscillation must shift to derive less lag through the structure and this forces the oscillation to a lower frequency. Eureka! We now have the mechanism which causes a decrease of frequency at the same time as the amplitude is increasing!

Oscillation Amplitude

Of course there is an interaction of the amplitude and phase between the structure and the line, but the end condition for a steady amplitude of oscillation is shown as

point 2 on Attachment II. Here the frequency of the oscillation is such that the decreased phase lag of the structure matches the increased phase lag of the line to preserve zero loop phase. The amplitude of the oscillation is such that the phase lag derived from the line (due to the amplitude related non-linearity) just matches that derived from the (linear) structure at the frequency of oscillation.

Incidentally, Attachment II shows that point 2 has a higher gain in the LOX line block due to lower resonant frequency. This is unimportant to this theory. The important point is that the line is detuned enough to contribute the phase lag subtracted from the structure block by going to a lower frequency of oscillation.

Stability of Oscillation

Let us examine if point 2 represents a stable operating point. If the oscillation frequency drops below that of point 2, the reduced structures gain would reduce the line excitation which would give less phase lag across the line which would call for more phase lag across the structure which would increase the frequency back to point 2. If the frequency of oscillation rises above that of point 2, the increased structures gain would increase line excitation, increase line phase lag, call for reduced structures phase lag, and cause a reduction of frequency back to point 2. Therefore, point 2 represents a stable operating point because frequency shifts above or below this point returns the oscillation to this point.

The amplitude, frequency and time characteristics of the oscillation buildup do depend on the initial starting point 1. If point 1 is to the right of the structural resonance, the initial decrease of frequency will be accompanied by increased structural gain. This will accelerate the process and may lead to points of inflection on the time histories of amplitude and frequency.

Changes of Structures Gain

We have tracked an increase in structures gain from stability to instability. Let us now consider a further increase in structures gain. This would be represented by a higher magnitude curve in the structure block of Attachment II without a (significant) change in the phase curve. This increased structures gain will increase the line excitation, cause more phase lag across the line, call for less phase lag across the structure, require a lower frequency of oscillation which produce somewhat less structures gain on the new gain

characteristic. This process will converge on a new stable point which is lower in frequency but has higher oscillation amplitude than the starting point (before the increased structures gain). The significance of this is that the oscillation of the unstable system will (approximately) track the structures gain characteristic.

Amplitude Jump Phenomenon

Thus far we have only used the non-linear compliance characteristic which indicates that the phase shift is a function of the forcing function amplitude. As mentioned under the Fourth Observation and shown in the sketch of that section, the larger amplitudes of forcing function have double-valued "frequency response" curves. For specific combinations of forcing function amplitude and frequency (points of vertical slope on the sketch) both the ac and dc outputs can suddenly increase with a small increase of forcing function.

Such a jump phenomenon introduces a great deal of phase shift; the operating point moves from the low frequency side of "resonance" to the high frequency side. According to the previously stated part of this theory, this increased phase lag again causes a reduction in the oscillation frequency while the system is diverging (from the lower amplitude of oscillation to a higher amplitude). But the frequency reduction and amplitude buildup now have a scale and time rate which is related to the jump phenomenon.

The fact that the amplitude jump increases the "gain" of the line-pump combination means that the reduced frequency, higher amplitude oscillation can occur even with the lower gain contributed by the structure. This oscillation frequency is well down on the (lower frequency) side of the structures resonance.

Let us examine how this jump phenomenon would be manifest. In the presence of a low amplitude oscillation which had been tracking the monotonically increasing frequency of a structures mode, we would approach the vertical slope point of the sketch from the left. Once we jump to the upper branch, the system responds with a lower frequency of oscillation. This will move the operating point to the left and could approach the other vertical slope point. If this happened, there would be a sudden reduction (negative jump) in the output, which would decrease the phase shift, increase the oscillation frequency and again approach the first vertical slope point from the left. Conceivably the system could hang up in this loop until some system parameter (e.g. a structures mode) changed enough to break out of this loop.

If the frequency reduction, caused by the initial amplitude jump, does not reach the second vertical slope point, the operating point stays on the upper response curve. Further increases in the structures resonant frequency will move the point to the right. If the gain of this structures resonance reduces, the forcing function will have reduced amplitude and the operating point will drift downward to one of the curves with less non-linearity. In returning to stability the oscillation may or may not have a negative jump depending on the exact relation of the frequency-gain characteristic of the structures mode.

Restatement of the Theory

The foregoing description of the theory can be restated in terms of the Nyquist plot, introduced under the First Observation. Consider a Nyquist plot in which a specific structures mode is a defined lobe which falls just to the left of the (1,0) point.

If the loop gain and/or phase change slightly to enclose the (1,0) point, the system becomes unstable. The diverging oscillation amplitude will increase the phase lag across the line-pump and this will rotate the Nyquist plot clockwise. This would tend to rotate the structures loop past the (1,0) point and return the system to stability (because the locus would no longer enclose the point). But it is the presence of the oscillation which rotated the locus. Therefore, the rotation stops when the locus passes through the (1,0) point. This zero-phase and unity-gain condition sets the amplitude of oscillation. Therefore the Nyquist locus must be interpreted not as a ratio of output to input, but as the (fundamental component of) output for a specific input amplitude.

This clockwise rotation of the locus will cause the intersection of the structures lobe and the positive, real axis to occur at lower frequencies. Again we have it--a decrease of frequency during the amplitude divergence!

The amplitude of the oscillation is fixed when the locus passes through the (1,0) point, and this is seen to be a stable operating point as follows. If the oscillation amplitude suddenly increases, this will cause additional phase lag across the line-pump and further rotate the locus clockwise. But this will uncover the (1,0) point which will have a stabilizing effect on the system, causing it to decay from this increased amplitude of oscillation. The decaying amplitude of oscillation will reduce the phase lag and undo some of the clockwise rotation of the locus. This process stops when the locus reaches

the (1,0) point and thus the pre-disturbance oscillation amplitude is re-established. A similar argument holds if the oscillation amplitude suddenly decreases.

A time-dependent increase in structures gain would increase the size of the structures lobe and move the locus to the right of the (1,0) point. This de-stabilizing effect would increase the oscillation amplitude, increase line-pump phase lag and increase clockwise rotation of the locus. The new operating point (when the locus again passes through the (1,0) point) will occur at a somewhat lower frequency but with an increased oscillation amplitude. Thus we (approximately) track the structures gain characteristics.

The amplitude jump phenomenon follows the process of the previous paragraph but it is more rapid. One could almost visualize the replacement of the pre-jump locus with a grossly different post-jump locus which accounts for increased size (gain) and phase lag. Both loci pass through the (1,0) point but the post-jump locus leads to an oscillation of much higher amplitude and lower frequency.

The eventual return to stability would have decreasing locus size with (relatively) less phase lag. Whether this return has a negative jump still depends on the detailed characteristics of the "frequency response" curves sketched in the Fourth Observation section.

THE SA-507 EXPERIENCE

The "footballs" of SA-507 are shown on Attachment III, also taken from Reference 1. They have the same characteristics as the initial part, called zone one, of the SA-508 POGO oscillations.

During the earlier periods of flight, there is a sequence of modes whose gain characteristic takes on a broad maximum as the modal frequency moves across the 16 Hz region. These "footballs" have been associated with this feature of the structures. The concept that they were the noise-excited filter response of a stable system was unsatisfactory since the signals appeared in the chamber pressure. The concept that they were the transient response of an unstable but time-varying system was less than satisfactory because the time variations were so slow that the unstable system should have diverged.

These "footballs" can be explained by the non-linear phase shift characteristics of the new theory. If the system is only slightly unstable (at a frequency near the resonant

peak) then the condition of zero loop phase can force the oscillation to a frequency of reduced loop gain. But reduced loop gain would tend to stabilize the system and reduce the oscillation amplitude. Therefore an equilibrium condition is derived with low amplitude oscillations and with very little non-linear effects. Even though small, the theory would predicate some decreased phase lag through the structure and a small decrease of oscillation frequency below the modal frequency.

This last point of a decreased frequency may be visible in a certain feature of Attachment III. The first three footballs which end with the system returning to stability (the fourth one stops due to center engine shutdown) have contour lines at their terminations which have an upward curvature. This could be the oscillatory frequency returning to the modal frequency, i.e., that the oscillation did not cause a frequency reversal but only delayed the frequency increase.

THE SA-504 EXPERIENCE

The mysterious characteristics of SA-504 POGO, Attachment I, can now be explained by both the non-linear phase shift characteristics and the amplitude jump phenomenon of the new theory. The SA-504 POGO signals are similar to the second part, called zone two, of the SA-508 POGO oscillations.

POGO occurred near the end of burn on SA-504 when one of the (lower) LOX tank modes coalesced with the engine truss mode to form a high gain mode. The POGO frequency started on the modal frequency but rapidly fell as the amplitude increased. The rapidity and magnitude of the amplitude and frequency changes suggest that the non-linearity of the cavitation compliance placed the operating point at the vertical slope point of the "frequency response" curves. There is further evidence of this in that the pump inlet pressure tranducer showed a sudden reduction in dc bias. After this jump, a stable oscillation point seems to have been obtained and the oscillation then tracked the structures gain characteristic, that is, there is a slow reduction of oscillation amplitude without a negative jump as the oscillation frequency gradually returns to the modal frequency. This can be seen on Attachment IV taken from the April 23 presentation of the Space Division of North American Rockwell.

SA-503 had a POGO history very similar to that of SA-504 except that it had a more pronounced period of low amplitude oscillations (zone one) before the rapid amplitude and frequency changes (zone two), and it maintained the high amplitude of oscillation for a longer period of time. Also the return to stability (see Attachment IV) appears to be a negative

jump. Since the theory relates the POGO characteristics to the structures, it should be mentioned that there were many structures changes between the heavyweight S-II-3 and the lightweight S-II-4.

It should be noted that a quantitative verification of this theory should show that the sudden reduction of frequency (0.9 Hz and 0.6 Hz on SA-503 and SA-504) can be accommodated within one structural mode. This will be easier to show if the initial point 1 is to the right of the resonant peak. Also the Martin-Denver presentation at the April 23 POGO Working Group Meeting indicated that an initial valve of structural damping of 1.5 percent increases to 4.0 percent for the 12 g's of oscillation experienced on SA-503 and SA-504. This should increase the bandwidth and allow a larger frequency shift within one structural mode.

The fact that these frequency shifts results in a lower gain across the structure must be examined in light of the increased gain across the line-pump combination due to the amplitude jump.

THE SA-508 EXPERIENCE

It is generally agreed that the zone one periods of POGO on SA-508 are similar to those of SA-507 and that the zone two phase of the 330 second POGO event was similar to that of SA-504, so the only question is why did the zone three period on SA-508 diverge so violently. It should be mentioned that the theory does not supply an explicit reason for this divergence, but it does furnish a frame of reference within which the explicit reason might be found. In fact, it tends to discount the generally accepted concept,which it is related to the engine, in preference to a new concept which is related to the structure (engine truss).

While the SA-507 and SA-508 "footballs" were similar to each other in earlier flight phases, the SA-508 oscillation was some 25% larger than SA-507 at 330 seconds and (because?) the ullage pressure was several psi lower. These small differences might explain why the SA-508 oscillation progressed into a zone two phase while SA-507 did not. The triggering of the amplitude jump might be a sensitive function of many variables, but once it is triggered, there is no question of its effect.

As mentioned previously, an increase in structural gain, or the gain of any element in the loop, would lead to an increased oscillation amplitude and a decreased oscillation frequency. If this higher oscillation amplitude leads to further increases in the gain of the offending component, the effects

are cumulative and the conditions are set for a major divergence (even though the decreasing frequency is reducing the gain of the structures mode).

The Rocketdyne hard cavitation theory that the violent divergence of zone three was triggered by an amplitude-sensitive gain change in the pump-engine system received general agreement at the April 23 meeting. Of course, one derives an increasing gain ratio by dividing the increasing chamber pressure measurement by the saturated signal of inlet pressure. Also steady-state pump characteristics would indicate an increased ac gain when an increasing inlet pressure oscillation sweeps over the knee of the ΔH vs NPSH curve. But it would be satisfying if we could derive a more physical reason which relates the vibrating pump and its supported column of LOX. What we need is a definite break point between the line-pump gain (in terms of pump discharge flow per unit of pump acceleration) for a certain value of cavitation and/or pump vibration and the gain for a slightly larger value.

Perhaps the answer lies in the fact that this is a two stage pump, namely, an inducer stage and an impeller stage. Perhaps at the lower levels of oscillation the vibration-induced cavitation is eliminated by the head rise across the inducer and the vibrating impeller does not introduce any further cavitation. Perhaps at higher levels of oscillation the inducer cannot supply adequate head rise, or equivalently supplies cavitating (or near cavitating) LOX to the impeller stage. If this causes the impeller to participate in the cavitation generation, we now have a new physical process which could significantly increase the output flow perturbations, that is, increase the gain.

An alternate theory to describe the zone three divergence is suggested by that used to describe the zone two event. Perhaps there is another non-linear spring which leads to double-valued "frequency response" curves and the second possibility of an amplitude jump phenomenon.

Consider the engine truss. During zone two oscillation the truss sees ±12 g's which, when added to the dc thrust load, approach the yield strength of the beam. Zone three oscillation was accompanied by a frequency reduction of more than 2 Hz. While normally this would be too large a frequency spread to associate with a single structural mode, the beam vibrations

of ±34 g's were close to its ultimate limit. Under such conditions there would be a large increase in damping and consequent widening of the frequency response.

The shape of the stress-strain curve between yield and ultimate connotes a "soft" spring which would lead to "frequency response" curves bending to the left, as shown in the sketch under the Fourth Observation. The non-oscillation operating point on the stress-strain curve is biased due to the dc thrust load. This makes the "spring constant" function non-odd and should lead to a dc bias which is a function of the oscillation amplitude.

It may prove very difficult to use the flight data to select between the unknown amplitude-triggered "gain" increase in the pump and the more familiar non-linear stiffness of a structural beam. This is due in part to the failures of the pump inlet pressure transducer at the critical time (if indeed the measurement would be meaningful under these conditions). Perhaps an examination of the dc shifts would help. If the zone two divergence is due to a (non-odd) non-linearity of the line-pump combination, the reduced dc bias should appear in chamber pressure and (unfortunately) also in the beam acceleration (or load). If the zone three divergence is due to the non-linear stiffness of the beam, the dc bias change should appear on the beam but not in the chamber pressure. However, it may prove difficult to distinguish in time the bias due to zone two from that of zone three, if indeed the transducers respond to dc. Another possibility would be to examine the waveforms to identify the non-harmonic overtones of the beam vibration.

At this point we can only suggest that there are two possibilities to explain the zone three divergence: line-pump gain non-linearity and non-linear stiffness of the center engine truss.

CONCLUSIONS

A simple statement of theory is as follows. Cavitation caused by pump vibration is non-linear, it adds compliance to the line and it increases the phase lag around the loop. In a diverging system the increased phase lag across the line is compensated by decreased phase lag across the structure. Thus we get decreasing frequency with increasing amplitude of oscillation at the onset of an instability. This cavitation non-linearity can lead to a steady amplitude of oscillation. At certain amplitudes of vibration, the response curve is double-valued and can produce an amplitude jump phenomenon. This

accelerates the decreasing-frequency, increasing-amplitude transient and results in a large amplitude of steady-state oscillation.

While the details of this theory were pieced together by the three of us, we did use the results of many other people and benefited from private conversations. Actually the theory is not very startling, and a review of the handouts of the POGO Working Group Meeting shows its near emergence in several places. It does not contradict nor grossly modify any of the previous results. What it does is to supply a framework into which all the pieces can be placed to form an overall picture.

It is readily admitted that at this point the theory is largely qualitative, and we do plan to pursue a quantitative evaluation of it. A more thorough and timely evaluation could be obtained if other people used it to examine their findings. There are several obvious points to be checked: where on the structural mode was the initial oscillation frequency; what damping is necessary to keep the observed frequency shifts of SA-503, SA-504 and SA-508 associated with one structural mode; does the decreased phase lag between the chamber pressure and the structural acceleration match the increased phase lag between the structural acceleration and the pump inlet pressure.

While the theory was derived to explain the S-II POGO, it might also explain the amplitude-limited features of the S-IC POGO of SA-502. Perhaps someone will want to examine those data for frequency delays and phase shifts.

J. J. O'Connor

2031-JJO-ajj J. J. O'Connor

Attachments

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2. J. J. Stoker, Nonlinear Vibrations In Mechanical And Electrical Systems, Interscience Publishers, Inc., New York, N. Y., 1950.

3 K. Klotter, "Steady State Vibrations In Systems Having Arbitrary Restoring And Arbitrary Damping Forces," Proceedings of The Symposium on Nonlinear Circuit Analysis, New York, N. Y., 1953.

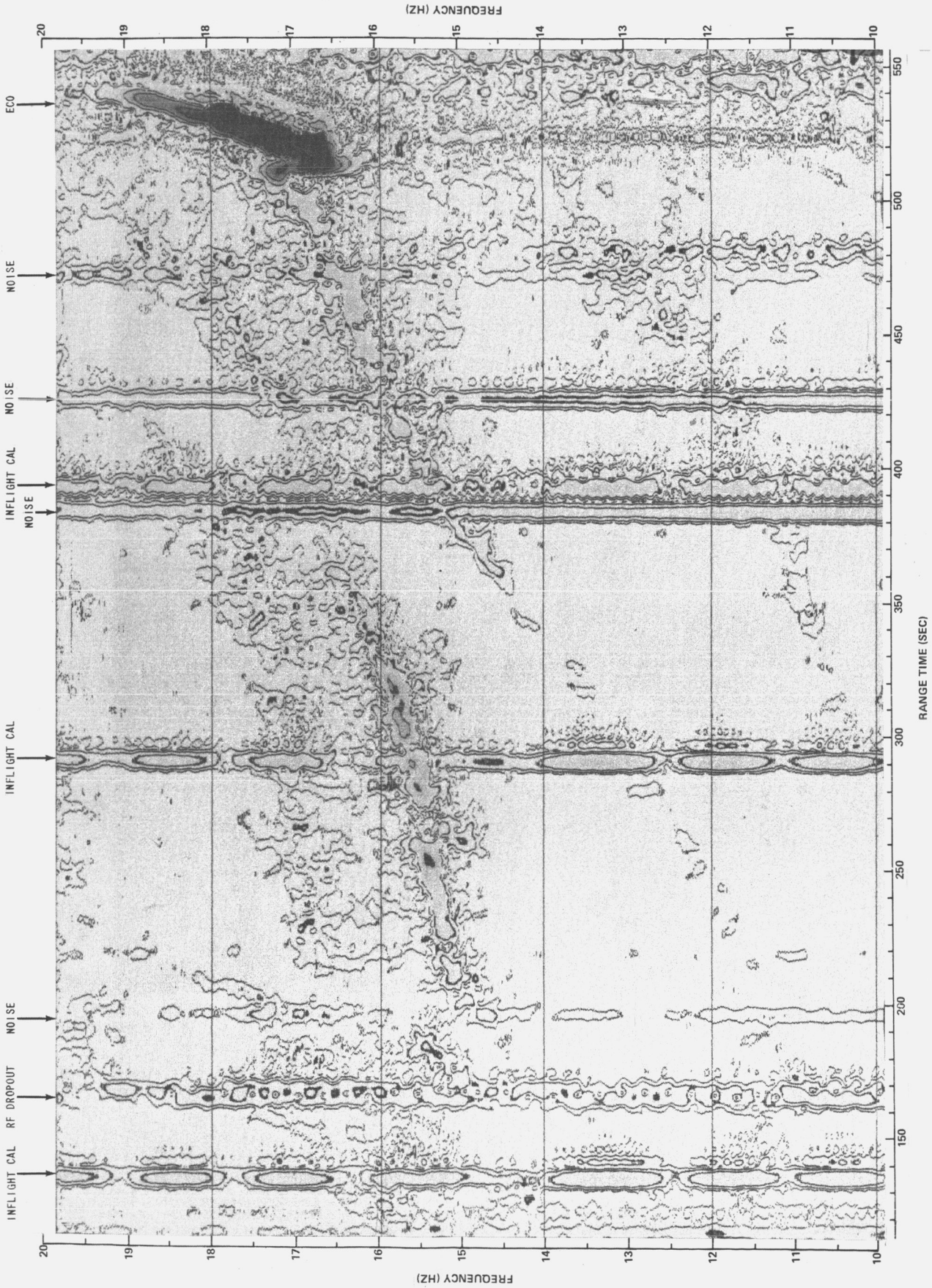
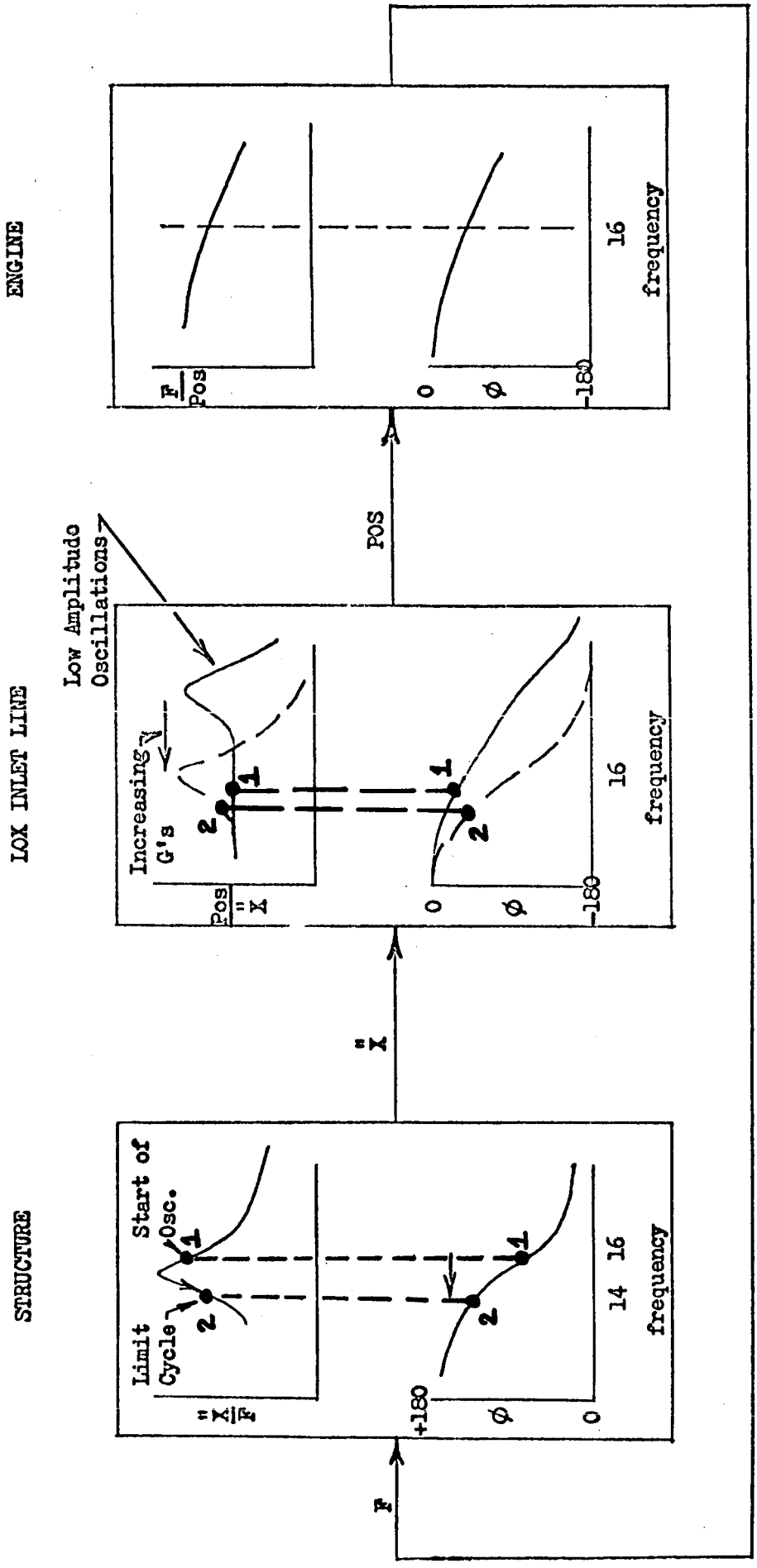


FIGURE 1c - SA-504 S-II E362-206 LOX SUMP PREVALVE LONGITUDINAL VIBRATION

ATTACHMENT II



POGO LIMIT CYCLE MECHANISM

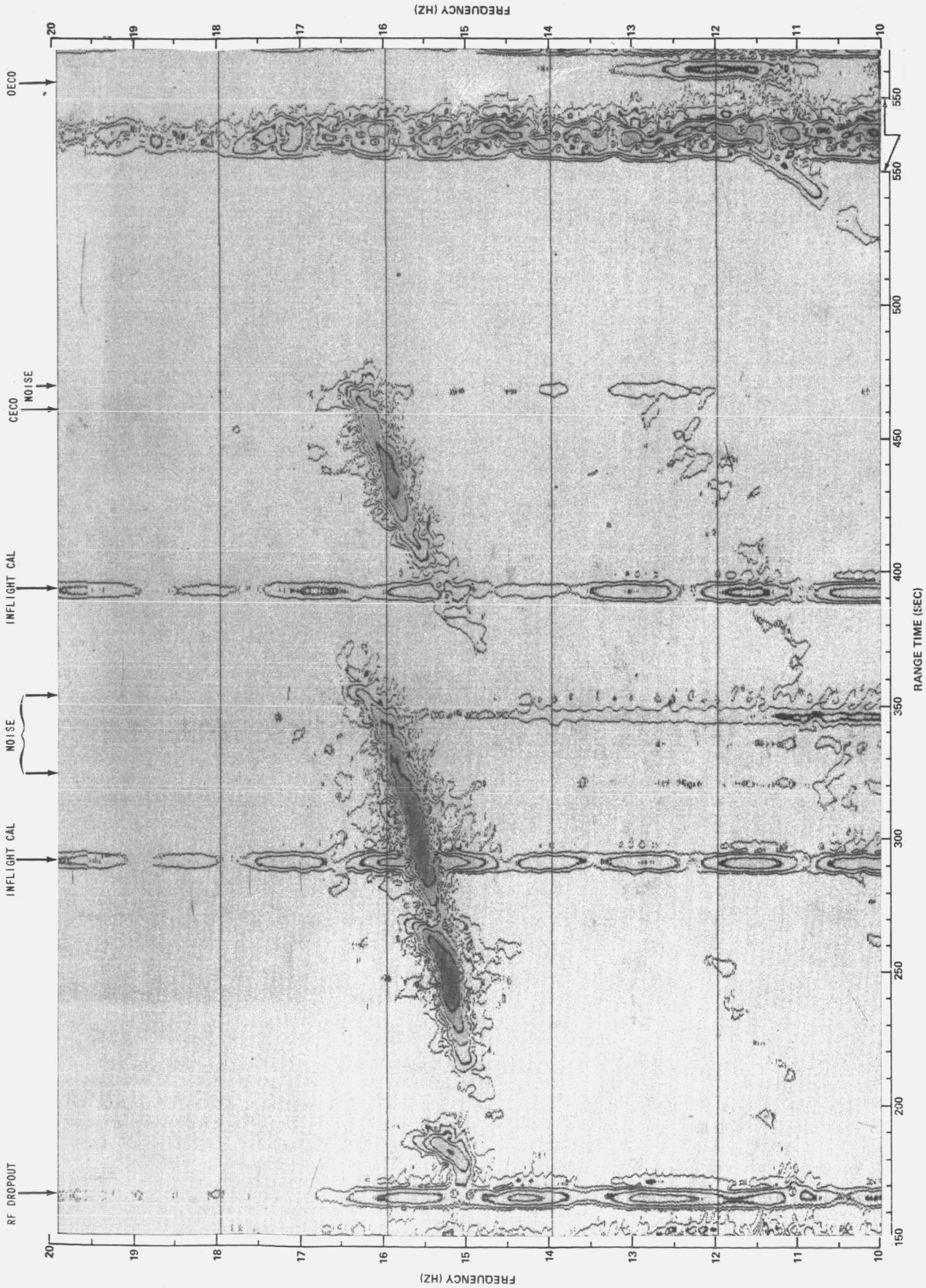
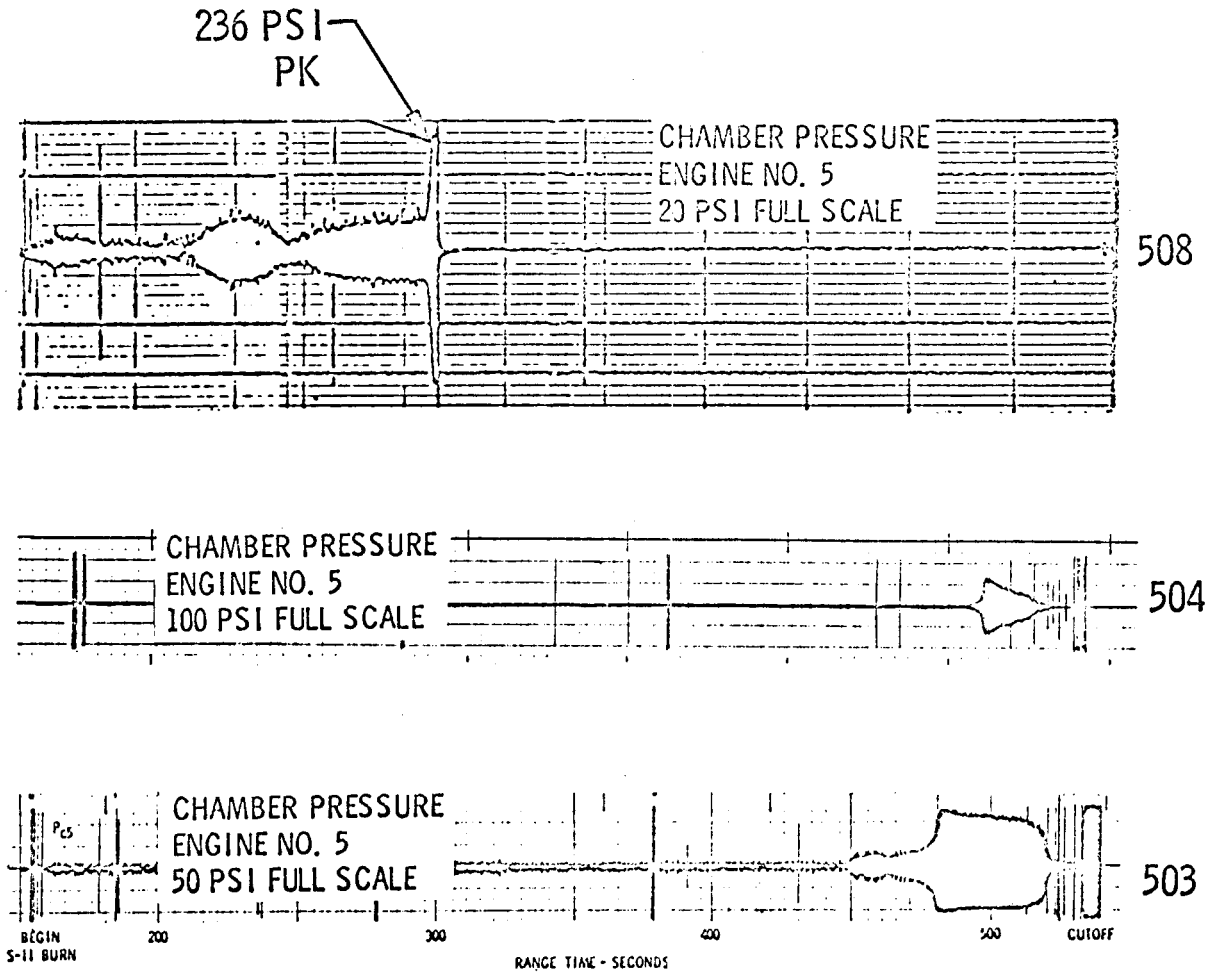


FIGURE 4e - SA-507 S-II E362-206 LOX SUMP PREVALVE LONGITUDINAL VIBRATION

CHARACTER OF ENGINE 5 CHAMBER PRESSURE OSCILLATIONS AS-503, AS-504, AS-508



ATTACHMENT IV

BELLCOMM, INC.

SUBJECT: A Theory of S-II POGO
Case 320

FROM: J. J. O'Connor

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