Figure 9. - Effect of suction line length. Injector pressure-drop ratio, 0.140.

TABLE II. - EFFECT OF PUMP-DISCHARGE-LINE LENGTH ON SYSTEM RESPONSE

[Injector pressure-drop ratio, 0.073.]

<table>
<thead>
<tr>
<th>Discharge-line length, ft</th>
<th>Chugging frequency, cps</th>
<th>Beat period, msec</th>
<th>Maximum peak-to-peak pressure-head perturbation amplitude after 0.6 sec, ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>416</td>
<td>(a)</td>
<td>0.33</td>
</tr>
<tr>
<td>3.6</td>
<td>385</td>
<td>50</td>
<td>.8</td>
</tr>
<tr>
<td>4.2</td>
<td>345</td>
<td>53</td>
<td>31</td>
</tr>
<tr>
<td>4.8</td>
<td>294</td>
<td>56</td>
<td>66</td>
</tr>
<tr>
<td>5.4</td>
<td>276</td>
<td>58</td>
<td>75</td>
</tr>
<tr>
<td>6</td>
<td>255</td>
<td>59</td>
<td>30</td>
</tr>
<tr>
<td>6.6</td>
<td>233</td>
<td>63</td>
<td>16.3</td>
</tr>
<tr>
<td>7.2</td>
<td>220</td>
<td>70</td>
<td>6.7</td>
</tr>
<tr>
<td>7.8</td>
<td>203</td>
<td>60</td>
<td>1.9</td>
</tr>
<tr>
<td>8.4</td>
<td>357</td>
<td>(a)</td>
<td>2.0</td>
</tr>
<tr>
<td>9.0</td>
<td>328</td>
<td>75</td>
<td>3.5</td>
</tr>
</tbody>
</table>

*No definite beating pattern.*
Figure 10. - Effect of discharge-line length. Injector pressure-drop ratio, 0.073.
is considerably influenced by the length of the pump discharge line. This system appears to have maximum instability with a discharge-line length of 5.4 feet, and it appears to be completely stable with a line length of 3 feet.

**Effect of Chugging-Suppression Device**

The stability of the reference combustor - feed system (with zero dome compliance) was determined with the chugging-suppression device attached to the midpoint of the discharge line. The resistive-shunt device had a resistance of 620 feet per cubic foot per second and a compliance of $0.8 \times 10^{-6}$ cubic foot per foot. The neutral stability condition for the reference system without the suppression device occurred at an injector pressure-drop ratio of 0.140. With the suppression device attached to the pump discharge line, the system was effectively stabilized to much lower values of injector pressure-drop ratio. As an example, figure 11 presents digital plotter traces for the combustion-chamber pressure computed with and without the suppression device for an injector pressure-drop ratio of 0.05. Even at this low injector pressure-drop ratio, the system, with the suppression device attached, is near the neutral stability condition. Examination of the pressure trace in figure 11(b) shows that the 250-cps chugging instability evident in the trace of figure 11(a) is effectively suppressed by the device. The small remaining disturbance in figure 11(b) corresponds to the next higher discharge-line mode, namely, the full-wave, 500-cps resonance.

![Figure 11](image-url)
The small instability appearing at 500 cps (in spite of the suppression device) can be explained as follows: As a pressure-sensitive device, the accumulator is ineffective if located at a point in the line where the pressure perturbation approaches zero. This condition may exist at a frequency that makes the distance from the injector to the suppression device a half wavelength (or multiple). If this frequency coincides with one of the lightly damped, natural frequencies of the feed system and if it falls in the range in which the combustion-chamber impedance is negative, an instability can occur. This circumstance was overlooked when the device was located precisely at the midpoint of the discharge line (in order to suppress the 250-cps mode) and accounts for the presence of the 500-cps instability in the trace of figure 11(b). This difficulty can be overcome by locating the accumulator at a position slightly less than a half wavelength from the injector at the highest frequency of the first interval in which the combustion chamber impedance is negative.

CONCLUDING REMARKS

It has been shown by an example that consideration of propellant-feed-system dynamics can significantly affect the analytical prediction of stability limits, chugging frequencies, and other response characteristics for liquid-rocket engine systems. The importance of the feed-system dynamics in any given stability analysis is dependent on the amount of compliance (fluid and structural) present in the injector-dome region of the system being modeled. When the dome compliance is sufficiently high, the feed system will be effectively uncoupled from the combustion chamber, and consideration of feed-system dynamics in a chugging stability analysis is not necessary. In many practical situations, however, it is likely that the injector dome will be sufficiently hard that feed-system dynamics will be an important consideration. In these cases, omission of a detailed feed-system model from the stability analysis may lead to an over-conservative design.

The example of this report demonstrates that the wave-plan method provides a useful analytical tool for a distributed parameter representation of a propellant feed system at chugging frequencies. It also indicates that certain simplifications of feed-system geometry may be possible when modeling a particular system - regardless of the analytical technique used. In the system analyzed in this report, the feed system above the pump could have been neglected with no significant change in the predicted stability limits or chugging frequencies. It is likely that this would be true for many operational systems. Also, the presence of pump-inlet cavitation in operational systems would most likely preclude the excitation of the higher suction line resonant modes (which result in beats). In pressure-fed propellant systems (no turbopump), the higher modes may appear in the system response if the feedline is sufficiently long.
The results of this study further indicate that, for systems with sufficiently hard domes, the designer may be able to improve the stability substantially by small variations in certain discharge-line hydraulic parameters. In addition, resistive-shunt or other types of chugging-suppression devices can be incorporated into a system and their effect readily analyzed by the methods presented in this report.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 14, 1966,
128-31-06-09-22.
APPENDIX A

FINITE-DIFFERENCE FORM OF COMBUSTION-CHAMBER EQUATION

The equation (eq. (17) of ref. 9) relating combustion chamber pressure to flow through the injector is

\[
\frac{d[H_c(t)]}{dt} + \frac{H_c(t)}{\theta_g} = \frac{C^*}{A_T \theta g} Q_i(t - \tau)
\]

where \( H_c \) is the chamber pressure head, \( Q_i \) the injector flow rate, \( \theta_g \) the gas residence time, \( A_T \) the throat area of the engine nozzle, \( C^* \) the characteristic velocity, and \( \tau \) the dead time. In order to utilize this equation in the wave-plan analysis, it is necessary to express the derivative of the chamber pressure in finite-difference notation in terms of the working time interval \( \Delta t \). A second-order backward finite-difference representation for the derivative is

\[
\frac{d[H_c(t)]}{dt} = \frac{3H_c(t) - 4H_c(t - \Delta t) + H_c(t - 2\Delta t)}{2\Delta t}
\]

Substituting this relation into equation (2) gives

\[
H_c(t) = \frac{\frac{C^*}{A_T \theta g} Q_i(t - n\Delta t) + \frac{4H_c(t - \Delta t) - H_c(t - 2\Delta t)}{2\Delta t}}{\frac{1}{\theta_g} + \frac{3}{2\Delta t}}
\]

where \( n \) represents the number of working time intervals \( \Delta t \) making up the engine dead time. This equation is used to calculate chamber pressure in the injector subroutine of the digital program.
REFERENCES


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—National Aeronautics and Space Act of 1958

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