applied, steady-state plunger force required to start the oscillation were recorded, using various line lengths and diameters. One set of calculated points also is plotted in Figs. 5 and 6 for comparison of the theoretical with the experimental results.

As can be seen, the frequency of oscillation is high, probably as a result of air entrained in the oil. Air entrained in the oil would make the oil more compressible and thus lower the velocity of sound through it. The experimental frequency of oscillation, therefore, would be lowered.

It is of particular interest to note that the frequency of oscillation generally goes down when the length of the line is increased. This is reasonable since the resonant frequency of the oil column is lowered when the length of the line is increased. Also, the force required to start the oscillation increases rapidly when the length of the line is decreased because theoretically the system must be stable when the length of the line is reduced to zero.

A steady-state plunger force is required in order to set the valve steady-state operating point, which establishes the proper and particular partial derivatives in Equations [6] and [11]. For the experiments, this force was applied through a rubber band having a very low spring rate.

Conclusions

From the results of this study it can be concluded that the oil lines connected to the valve are a major factor in making an otherwise stable valve unstable. Therefore, to eliminate the instability, the oil lines should be (1) made as short as possible by moving the accumulator shown in Fig. 1 as close as possible to the valve, and (2) as dissipative as possible; also, adding a viscous damper to the valve plunger will help.

It is hoped that this analysis will give a basis for a better understanding of the phenomenon of valve squeal.

Discussion

Gerhard Reethof.[5] The author has made a very definite contribution to our understanding of one further mechanism of valve instability. This paper represents a fine example of the effectiveness of "cross breeding" between the tools of the electrical engineer as applied to the mechanical-engineers' problems. Attention should be drawn to work done in parallel and independently, of the efforts reported here, by Dr. F. D. Ezekiel[6] of the Department of Mechanical Engineering at M.I.T. Dr. Ezekiel's exhaustive work substantiates fully the author's results, yet presents some very effective means of eliminating valve squeal. Thus, splitting the "organ tube" into two separate sections of different diameter or any other method of isolating the valve from the organ tube or increasing the "organ-pipe" quarter-wave frequency has proved effective.

As the author points out, the forces acting on a spool valve in this type of oscillation are entirely flow-induced forces near the metering edge. The work presented here should be expanded to the serious poppet-valve problem where the all-too-familiar squeal or "singing" has been an embarrassment to hydraulic relief-valve manufacturers and users.

The test results presented by the author are in qualitative agreement with the results of the analysis. The fact that the frequency of oscillation increases with increasing tube diameter can be explained physically as follows: During oscillation a standing quarter wave is set up in the organ tube as shown in Fig. 7 of this discussion.

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[6] "Effect of a Hydraulic Conduit With Distributed Parameters on Control-Valve Stability," by F. D. Ezekiel, ScD thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Mass., June, 1955.

The node is outside of the tube and moves inward with increasing tube diameter. Thus the physical length of the tube does not equal the quarter-wave length of the pressure wave causing a certain disagreement between analysis and experiment.

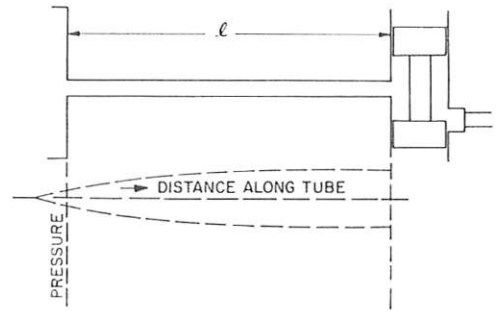

Fig. 7

The increase in frequency with increasing diameter also can be predicted from the analysis. Thus from Equation [6] and Fig. 3 of the paper the system becomes unstable when

$$Z_0 \left.\frac{\partial Q_v}{\partial P_v}\right|_{X_v} \tan \frac{\omega l}{V} = -1$$

Since

$$Z_0 = \frac{1}{A}\sqrt{\frac{\rho}{\beta}}$$

$$\frac{1}{A} \tan \frac{\omega l}{V} = \text{const}$$

Thus as A increases $\tan \omega l/V$ must increase, or the frequency increases.

J. L. Shearer.[7] The fundamental concepts employed by the author in gaining a better understanding of an important hydraulic-control problem are old and well known. Liquid column dynamics have been studied thoroughly in connection with water-hammer problems, especially in large power-generating installations where serious interaction takes place between the penstock and the turbine, load, and governor. Yet he seems to be the first person to have recognized the interaction between the hydraulic supply line and the control-valve spool in hydraulic-control systems. Of fundamental significance is the fact that the coupling "mechanism" is the flow-induced force of the hydraulic fluid on the valve spool, and that the thorough work done by S.-Y. Lee on fluid-flow forces in valves undoubtedly helped make it possible to recognize this problem and deal with it quantitatively.

Although the author does not deal with exhaust-line characteristics, it would seem that they might be equally important, although somewhat more difficult to analyze because of cavitation at low pressures.

In trying to eliminate hydraulic squeal it seems important to consider both parts of the system and to apply design techniques that will provide a proper match between the two parts of the system. Dr. F. D. Ezekiel[6] has shown in an M.I.T. Doctoral thesis that a number of things can be done to modify the system to make it stable. Of particular interest is his work on providing a sudden expansion or contraction along the supply line. Of course it would be desirable to eliminate completely the fluid-flow force on the valve spool, but to date this has not been done.

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It would seem that the results of this also could be applied to work with process-control valves, especially ones installed on long lines.

Author's Closure

The author wishes to thank Professors Reethof and Shearer for their able discussions of the paper, and for their discussions of the work done by Dr. Ezekiel at M.I.T.

There is little question that the important work of S.-Y. Lee on fluid-flow forces in valves made it possible to recognize this problem and deal with it quantitatively. In fact, this is a very good example of the progressive build-up of a science in which one piece of work leads to another. However, it must be confessed that the author was very dubious about using S.-Y. Lee's steady-state flow force work when dealing with frequencies up in the hundreds of cycles per second. This doubt was caused by the possible large time delay required to establish the steady-state fluid flow patterns before the force can build up.

The exhaust-line characteristics would appear in the perturbation equations undistinguishable from the high-pressure line characteristics. However, in practice, the exhaust-line would cavitate and limit the amplitude of pressure oscillation to a low value which, though not as violent as squeal, could rapidly erode away the valve metering edges (which is another problem). This is in contrast to the pressure oscillation in the high-pressure line which can reach the amplitude of the supply pressure and therefore be very violent, and was the most urgent problem.

The explanation for the discrepancy between the calculated and experimental frequency of oscillation sounds very plausible. However, to be somewhat technical, all of Fig. 3, rather than just the top block, should have been used to prove the point.