Plant Pulsation and Vibration Control

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Pulsations *per se* are not problems; the detrimental or undesirable effects of pulsations in piping and compressor systems are. Although the existence of pulsation-induced problems is rather well recognized by industry, these problems are not totally and universally understood. The major effects may be categorized as: (1) piping fatigue due to pulsation-induced vibrations, water hammer, etc; (2) pump or compressor cylinder performance degradation due to pulsation interaction between cylinder and piping; (3) airborne noise, especially for high-frequency pulsation; and (4) pulsation-induced errors in metering systems. Any discussion of piping pulsation soon becomes academic or sterile unless it includes consideration of these effects of pulsations.

Historically, the normal approach to controlling pulsation-induced vibrations is to install pulsation dampeners, suppressors, desurgers, volumes, etc., in the piping system to "strain out the lumps". The "black boxes" normally used to perform this function are usually some standardized design which has been shown to work at some particular installations and adapted from this to generalized use. Such an approach is rather hit-or-miss in nature, in that performance is extremely unpredictable.

The most serious limitation in design and use of off-the-shelf pulsation equipment is that no effective means is used for predicting the response of the total piped-up system in advance. The fact that a dampener works in one instance does not mean it will work in another. In those cases where vibration troubles do show up they can be disasterous. In other cases, the vibration reliability is improved but through sacrifice of cylinder performance and plant efficiency. A common approach is to build highly restrictive flow devices to "damp" pulsations. This usually gives some improvement in filtering, but in so doing, static pressure drop becomes excessive and operating costs suffer.

Commercial pulsation suppressors come in all sizes, shapes, prices, and designs. They are normally a combination of volumes, chokes, and sometimes perforations, slots, or other elements which allegedly improve suppressor performance. In contrast, Fig. 1 shows a relatively simple but very effective pulsation suppressor design, but one which can usually outperform commercial devices when properly designed for cut-off frequency and pass bands, and when properly matched to the rest of the compressor piping system.

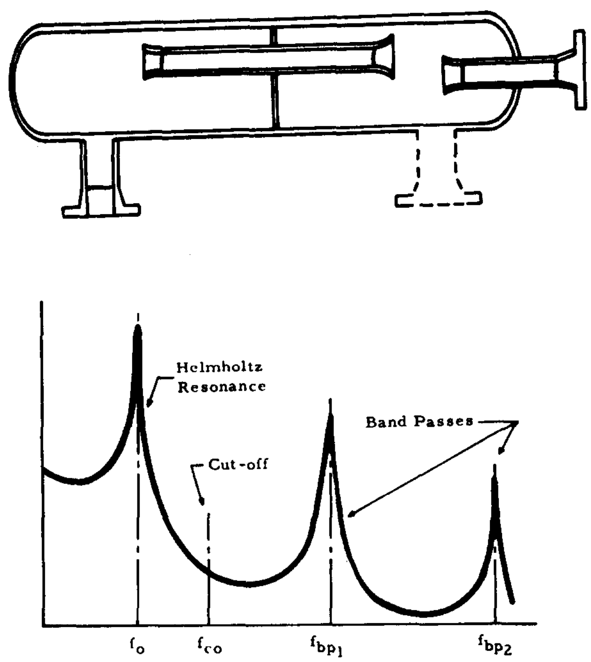


FIGURE 1

EXAMPLE OF LOW PASS FILTER DESIGN AND ACCOMPANYING RESPONSE

DESCRIPTION OF SGA COMPRESSOR SYSTEM ANALOG

In view of the important effects of pulsations on piping vibrations and in cylinder performance, the SGA Compressor System Analog

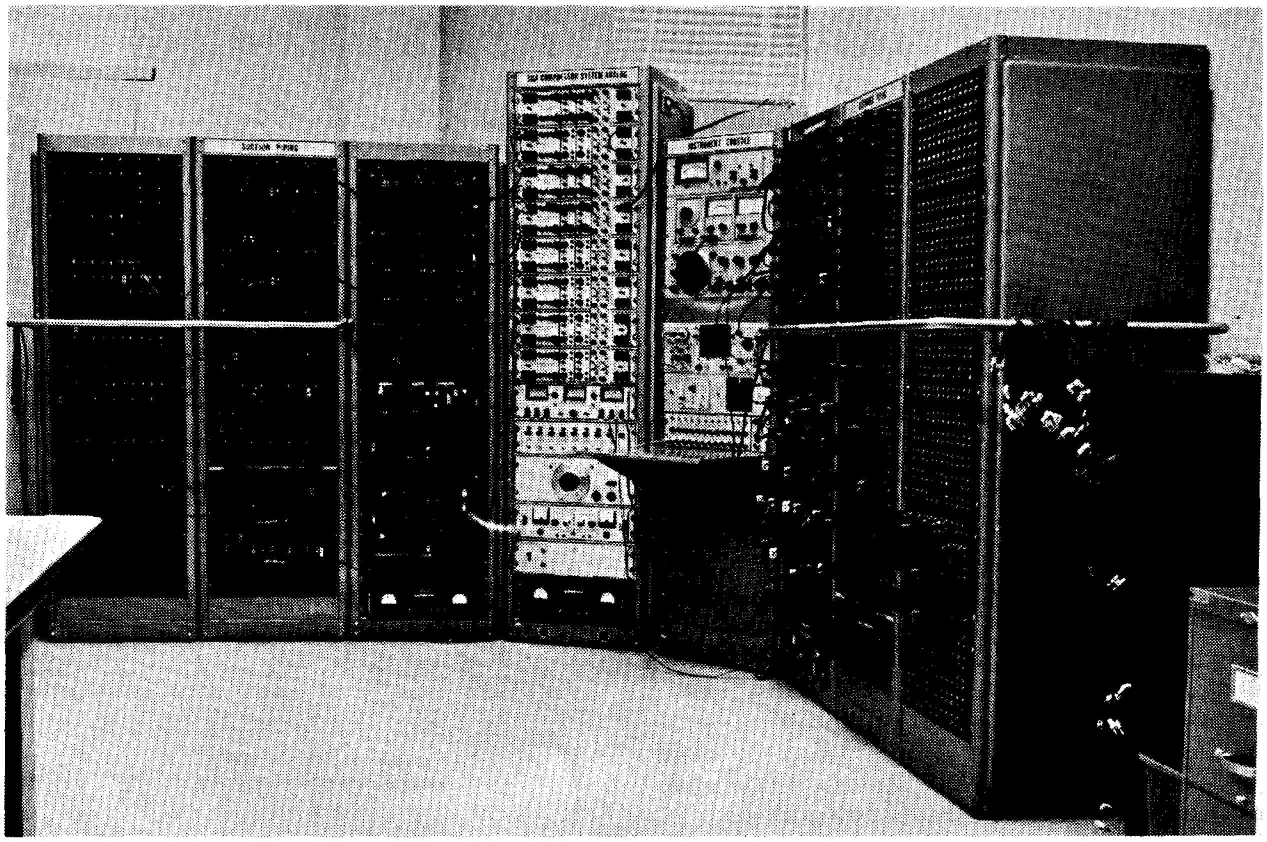


FIGURE 2

SGA ANALOG FACILITY

(Fig. 2) was evolved at SwRI in the early 1950's as a device for more effective design of pulsation control equipment and piping systems. This device has been described in detail previously in the open literature.[1]

In the simplest terms, the analog is a scaled electrical model of a compressor system including both compressor cylinders and piping system. The device is built as a block-by-block representation of the compressor system so that piping can be simulated merely by plugging in electrical "pipe section" analogs, and cylinders can be sized and phased as desired. Setup can be achieved for piping systems of arbitrary complexity, and any number and size of cylinders can be simulated, with any crank throw arrangement. Any fluid can be simulated, from hydrogen to heavy liquids.

Upon setup of the analog, operation is quite straightforward and analysis using the analog is directly analogous to running a field test. Obvious advantages exist, however, in that pressure (voltage) and flow (current) measurements can be made very simply anywhere in the system, and piping modifications can be made merely by changing delay line components. Figure 3 shows a typical delay line element, which can represent a section (e.g., one foot) of any size pipe, filled with any type fluid, under any pressure.

The heart of the system analog is the compressor cylinder analog which is shown in the center of the photograph in Fig. 2. This analog is composed of a number of double-acting compressor cylinder analogs which are devised to simulate the physical extraction of gas (in this case electrical charge) from the suction piping, raise it in potential or pressure, and discharge it into the discharge piping. The action of the analog itself is sufficiently similar to the action of the compressor cylinder that the pulsations spectrum dumped into both the suction and discharge piping is very carefully simulated. In addition, the more subtle aspects of piping influence on compressor efficiency (PV card) are accurately simulated. Using such an approach, if a complete station piping system is simulated on the analog, together with a proper compressor simulation where cylinders are adjusted to simulate proper bore, stroke, capacity and phasing, then a very accurate simulation of the entire compressor installation can be realized and conditions varied over any desired range of expected operating conditions. Suction and discharge pressures may be varied as desired as may be engine speed, fixed clearances, and the like. Using this device, a simulated field test of the plant can be run before the plant is ever built.

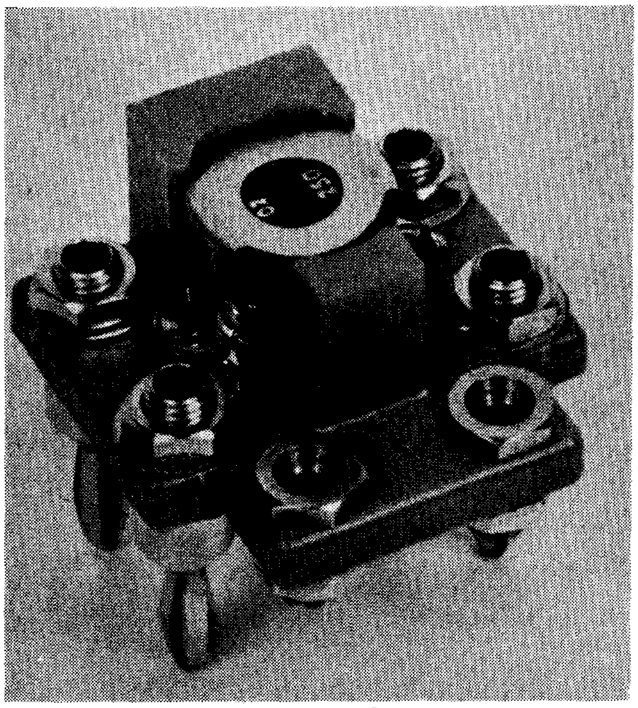


FIGURE 3

DELAY LINE ELEMENT

The analog provides the only known method for effectively predicting compressor pulsations as they are induced in the piping system and for evaluating the effect of this piping on cylinder performance. Examples of the data taken in such a study are shown in Figs. 5 and 6, to be discussed later.

The SGA Compressor System Analog has now become an accepted standard for compressor installation design. At SwRI alone it has been used in over 1800 studies for plant locations throughout the world. The map in Fig. 4 shows location of studies conducted through 1970.

As a result of the acceptance given the analog, the term "analog study" is now a rather common term within the natural gas and petrochemical industries. However, the nature of the work being done on these analogs has varied considerably over the past 15 years. Whereas early studies were largely limited to pulsation analyses with very little attention to the mechanical characteristics of the compressor-piping systems, they have now progressed to the point where the analog portion of the work is but a small element of the total system design process. As a result of the continuing research conducted by the SGA sponsor group at SwRI, design capabilities have been extended far beyond analysis and control of pulsations. As these total system design capabilities became available to augment the analog studies conducted at SwRI, the term "analog study" was still applied for convenience and in lieu of a more definitive description.

AN ANALOG STUDY

In view of the reliance industry is now putting on the analog approach to solve pulsation problems, some clarification is needed as to what an analog study consists of. In order to avoid any mix-up, therefore, we will define an "analog study" in accordance with the role it plays in plant design. Other design and analysis functions will be identified separately. This uniformity in terminology should help clear up ambiguities as to what is to be covered in a proposed system design study, define what component parts of the study will be provided, and more clearly indicate the range of design services available. With such a definition, a better chance exists for tailoring scope and depth of a study to the particular needs at hand. In many cases more than just an "analog study" is needed.

Two principal types of piping pulsation data are taken on the analog:

1. *Piping Passive Response* (see Fig. 5)—This is a swept frequency analysis of the acoustic response of a piping system. The result is an amplitude versus frequency plot of the transmission characteristics of a piece of a piping system; for example, from the compressor valve to some point in the piping system. This plot shows the frequency regions which are amplified and those regions which are attenuated. Of particular value, they show the acoustical resonant frequencies and resonant buildups which appear within the piping system.

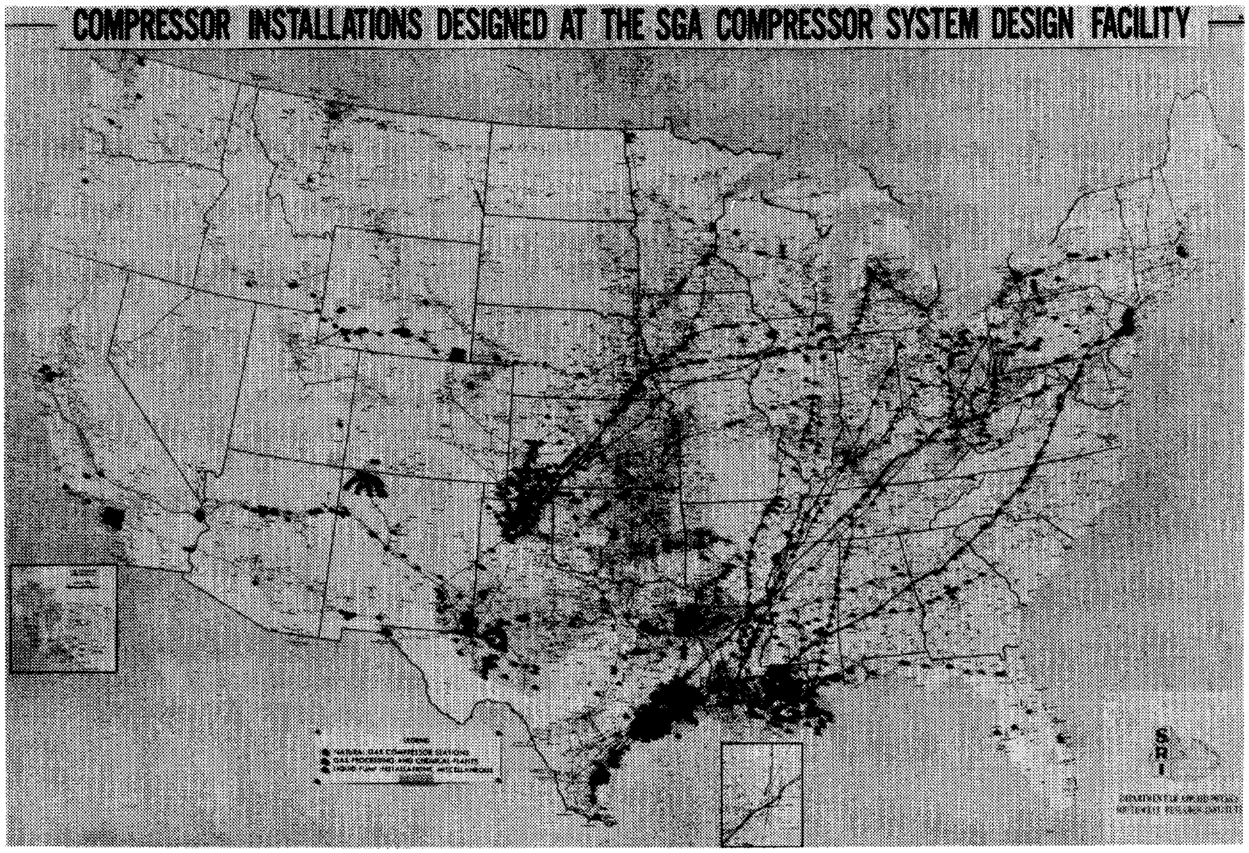


FIGURE 4

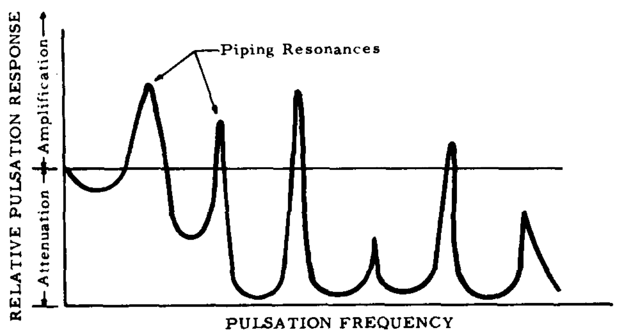
2. *Pulsation Analysis* (see Fig. 6)—If the pulsation spectrum generated by the compressor cylinder is introduced into a piping system, piping characteristics will amplify some pulsation components and attenuate others. A pulsation analysis shows the transmission of compressor pulsation frequency components from point to point in a piping system.

In addition, an analog study will show the effects of pulsation on the cylinder PV cards, and may or may not include a simplified analysis of mechanical system response. In the mechanical analysis, the three predominant low-frequency resonances of the compressor-manifold systems are computed, and a plot is made of the vibration sensitivity of the piping to shaking forces from zero up to several hundred Hertz. This plot is limited to vibration sensitivities parallel to the crankshaft and is technically a mechanical passive response curve. (See solid curve in Fig. 7)

PLANT DESIGN CRITERIA

The analog provides an accurate and accepted means for predicting piping pulsations in compressor and pump stations. In effect, a proposed plant can be field tested for pulsation and cylinder performance characteristics before it is ever built. However, as stated previously, determination of pulsations per se is not an end in itself. Rather, it is the effects of these pulsations on piping system stress that pose the most important problem. Plant design criteria should not be written for pulsations *per se* but rather for the various effects which these pulsations may have; i.e., for pulsation-induced vibratory stress levels to minimize pipe breakage problems, for compressor performance to control adverse interaction of the piping and compressor cylinder, for radiated noise from the piping system, and for metering accuracy.

Historically, many types of vibration and pulsation criteria have been developed on the basis of field measurement at existing plants. These normally involved pulsation or vibration levels taken at some unspecified point in the piping system. In addition to the fact that such criteria are fundamentally inaccurate and, in fact, fundamentally inapplicable to the determination of potential pipe fatigue problems, they are also after-the-fact criteria; i.e., there has been no way to use them until the plant was already in operation. Their use at the design stage requires an effective technique to predict both pulsation and vibration levels. Similarly, if more effective criteria are used involving piping stress levels, again prediction techniques are needed for pulsation conditions, and for predicting the effects these pulsations have on the piping or compressor system. A plant design study should not be limited to pulsation control and analysis *per se,* but should be oriented toward control of piping stress and cylinder performance through pulsation and vibration control.



INPUT: Constant Amplitude Swept Frequency Acoustic Signal

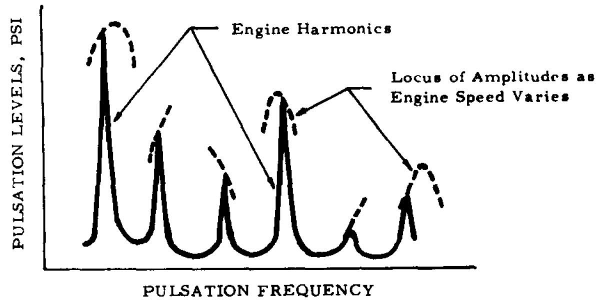
PLOT: Piping Passive Response from One Point to Another

FIGURE 5

ACOUSTIC PASSIVE RESPONSE OF A PIPING SYSTEM

MECHANICAL DYNAMIC ANALYSIS

While an accurate definition of piping pulsations is necessary to design a compressor piping system, it is of no more fundamental importance than accurately defining the mechanical response of the piping system. Theoretically, pulsation suppressors of sufficient size and effectiveness could be used to completely eliminate any significant pulsation amplitudes, but this approach becomes extremely cumbersome and expensive for typical compressor installations. Similarly, a mechanical system could be designed to withstand any pulsation forces, but again the problems of practicality and economics limit the effectiveness of this approach.



INPUT: Compressor Pulsations, Over Engine Speed Range

PLOT: Induced Pulsation Levels at Various Points in the Piping

FIGURE 6

COMPRESSOR PULSATION ANALYSIS

Thus, a complete analytical or simulation technique for defining piping system reliability under pulsating flow conditions should go beyond analysis of pulsations. A complete vibration analysis should include consideration of the shaking force into a piping system, the response of piping to this complex forcing function, a correlation of vibration response to induced piping stress, and evaluation of failure probability. In this procedure, the first step is to define shaking force on the piping based upon data from the analog study. These pulsations normally possess complex wave forms, and are made up of crankshaft frequency and harmonics thereof. This complex pressure wave reacts at various points within the compressor manifolds and piping systems. Care must be taken in accounting for the complex shaking forces in both suction and discharge piping, their relative phasing, and their point of coupling.

This force data is used as input into an analytical technique describing mechanical piping characteristics, and forced vibration response of the piping is computed. This analysis is repeated over a range of conditions to predict field vibration levels over the desired range of operating conditions. As in the case of pulsations, however, vibrations within them-

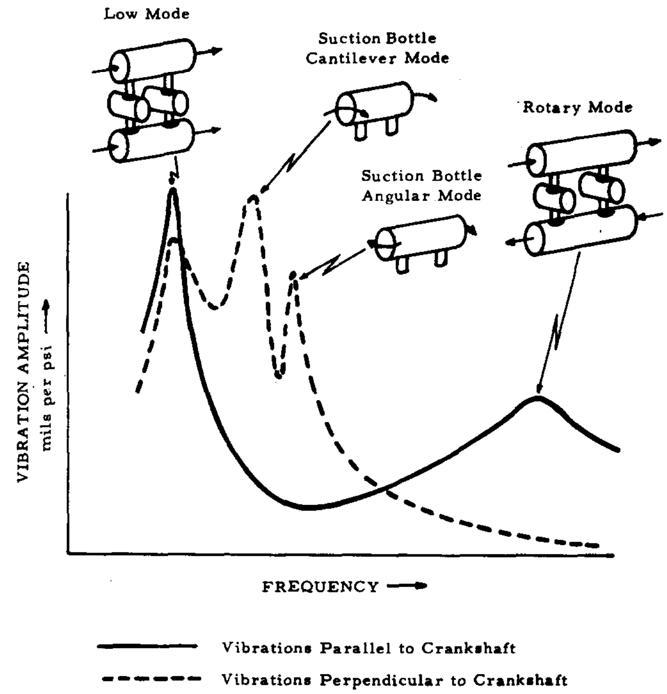


FIGURE 7

TYPICAL MECHANICAL PASSIVE RESPONSE OF COMPRESSOR PIPING SYSTEM

selves do not cause pipe failure—it is the stress which these vibrations produce at critical points in the piping. Hence the mechanical analysis program has been carried to the point of predicting these vector stresses resulting from the complex, multimode and multi-frequency vibrations being experienced. These stress levels are then used in conjunction with cumulative fatigue theory to predict safety or failure probability in the piping system. Specifically, this Mechanical Dynamic Response Analysis provides the following data:

1. Passive mechanical response: resonant frequencies, mode shapes, and damping, for modes both parallel and perpendicular to the crankshaft, (see Fig. 7)
2. Forced vibration amplitudes, frequencies and modes
3. Location of high stress points
4. Stress amplitudes due to vibrations
5. Safety evaluation relative to high cycle fatigue limits
6. Mechanical vibration control techniques: design and placement of piers and pipe clamps
7. Any piping design changes required to alleviate potential stress or performance problems.

MECHANICAL STATIC ANALYSIS

Static stresses in compressor piping systems can also produce significant stress levels, both from the standpoint of component failure and equipment misalignment. Included in the total system design process, therefore, are low cycle fatigue analyses for predicting forces and stresses due to thermal gradients and transients, pipe and fitting weights, static pressure, and bolt-up strains. Included in the design analysis are techniques for design of predictable thermal anchors and supports, and unique capabilities for including the torsional flexibility of pipe junctions and elbows. A major contribution of the SGA research in this area has been the more accurate definition of flexibility and stress intensification factors for a wide range of branch connection configurations normally used in compressor piping systems.

SYSTEM PERFORMANCE ANALYSIS

As noted previously, pulsations can degrade plant efficiency in at least two ways. First, commercially available pulsation suppressors often have inordinately high static pressure drop. This is by design, as high flow resistance is the method used to obtain pulsation attenuation for as wide a range of applications as possible. Alternatively, when suppressors are tailored for a particular application, the high pressure drops can be avoided while retaining equal or better pulsation control, providing an effective design technique is used. Almost any silencer will work if enough pressure drop is taken across it.

A second compressor inefficiency results from pulsation interaction of the piping and compressor cylinder. In this case, pulsations in the piping can seriously distort compressor PV card and significantly alter horsepower requirements, capacity, or both. This effect is similar in nature to tuned engine inlet tubes which can supercharge and increase cylinder power. Alternatively, if they are improperly designed or operating away from design speed, they can starve the engine. Thus an effective compressor system design should include consideration of the piping system as it affects system efficiency. The analog data can be used to analyze cylinder horsepower and capacity as a function of piping design and operating conditions and this data can be reduced to BHP/MMSCF.

Economic studies show that a design analysis which saves as little as one psi drop in a filter bottle will quickly pay for itself in fuel gas savings. Analytical techniques have therefore been evolved to improve the state-of-the-art in pressure drop prediction, with special emphasis on junctions, branches and configurations normally used in filter bottle design. This design service is now routinely available in conjunction with the analog studies, together with analysis techniques to quantitatively define the horsepower losses associated with piping system pressure drop.

COMPRESSOR MECHANICAL ANALYSIS

In addition to the design techniques described above, techniques have also been devised to handle other dynamic design problems associated with compressor installations. These problems include foundation design, shaft criticals and rod loading.

Foundation Design

Design of block and mat foundation systems are made from both static and dynamic considerations. In addition to the problem of adequately simulating the various vibratory modes present and the interaction of machine and foundation, this design process requires the input of data on dynamic and static soil properties. Field test techniques have now been devised for making such measurements.

Frame foundations as often found in chemical process plants and for centrifugal machines present a special problem in defining response of the three-dimensional frame structure. Again, the forced vibration response data are computed for the machine and its operating conditions.

In analyzing the forced dynamic response of foundation systems, consideration should be given to the amplitude and frequency of equipment shaking force, including rotating machine unbalance, shaft lateral criticals, and the like.

Shaft Criticals

This has become an especially important problem area, particularly for high speed rotary machines. Lateral shaft criticals are important causes of failure in bearings and compressor seals. Problems with torsional criticals usually involve broken shafts, couplers, or gears.

Analytical techniques are now available for determination of shaft critical speeds, and for assessment of field problems involving torsional or lateral vibrations, bearing instabilities (half-speed whirl, oil-whip resonance), and the like.

Whereas such problems seemingly have no direct relationship to pulsations, they can in fact be strongly influenced by flow instabilities. For example, studies have shown that low frequency pulsation from a reciprocating compressor plant can significantly affect performance of a centrifugal compressor. Head losses up to 25 and 30 per cent have been experienced in the presence of such reciprocating pulsations. Similarly, pulsations at a centrifugal can cause high frequency variations on the wheel which act as a source of torsional vibration excitation.

Rod Loading

The analog can also be used to provide rod loading data by measurement of instantaneous differential force (pressure times piston area) on either a single or double-acting compressor cylinder.

CONCLUSION

The study summaries described above constitute the present state-of-the-art for compressor installation design and for analysis of field problems in areas of vibrations and performance. The analog techniques described represent the only proven technique for analysis and prediction of compressor pulsation problems short of building the plant and making field measurements. The mechanical technology for dynamic analysis of the compressor system vibrations extend the analog analysis in describing the adverse effects which pulsations may have. These in turn are augmented by other analysis techniques for static and low cycle stress determination as these contribute to the overall fatigue problem.

With the design techniques now available, there is little excuse for building vibration and stress problems into a compressor plant, or for adverse pulsation effects on cylinder performance. The techniques described provide an effective means for anticipating potential problems at the plant design stage, and thereby provide a means for solving these before drawings are released for construction. The techniques have also found wide acceptance in solving problems as they show up in operating plants, as these facilities are expanded or changed, or as operating conditions change. With the backlog of experience on some 2000 plant design studies, the techniques described have gained wide acceptance and have played a significant part in the growth and increasing sophistication of compressor installations on a worldwide basis.

REFERENCES

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2. Nimitz, Walter: Pulsation Effects on Reciprocating Compressors. ASME Paper 69-Pet-30, Sept. 1969.