Vibration Transmission Studies of Flexible Pipe Connections   Report 2441

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

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Vibration Transmission Studies of Flexible Pipe Connections

By

Ronald C. Hirsch

MARINE ENGINEERING LABORATORY

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ABSTRACT

The results of studies of vibration transmission on three sizes of pressurized and unpressurized flexible pipe connections are presented. The connections include Dacron-lined and steel-braided hoses in "dog-leg" configurations and Electric Boat flexible pipe couplings in three-planar configurations.

Results showed that, generally, the Dacron-lined hoses exhibited lower vibration transmission characteristics than did the steel-braided hoses and Electric Boat flexible couplings. However, the Dacron-lined hoses showed a larger increase in vibration transmission between 20 and 800 hertz when pressurized, than did the other types of flexible connections in the same frequency range.

Results also showed that little difference existed between the magnitudes of transfer impedance for the three sizes of unpressurized Dacron-lined flexible hose.

ADMINISTRATIVE INFORMATION

This investigation was authorized by reference (a) under NAVSHIPS Sub-project S-F113 11 09, Task 03955, Assignment 72 105 630.

ADMINISTRATIVE REFERENCE

(a) NAVSEC ltr 39558/9480 ser 6648A3-1963 of 19 Aug 1966.

TECHNICAL REFERENCES

1. Hirsch, R.C., "Vibration Characteristics of Two Flexible Hose Types Arranged in a Right Angle Configuration," MEL Rept 288/65, Oct 1965.

2. Hirsch, R.C., "Vibration Transmission of Flexible Pipe Couplings Influenced by the Elements of a Trim-Pump System," MEL Rept 263/66, Sep 1966.

3. Smith, J.E., "Final Report on the Development of Analysis Techniques for Submarine Machinery Installations by Mechanical Impedance Methods," PNS test T819-030, Sep 1963.

4. Smith, J.E., "Computation Techniques for Mechanical Impedance Methods," 35th Shock and Vibration Bulletin, NRL, Apr 1966.

5. Darby, R.A., "A Practical Method for Predicting Acoustic Radiation or Shock Excursions of Navy Machinery," 34th Shock and Vibration Bulletin. NRL, Dec 1964.

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NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

VIBRATION TRANSMISSION STUDIES OF FLEXIBLE PIPE CONNECTIONS

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INTRODUCTION

The design of flexible pipe connections that will possess structural integrity and good vibration attentuation properties presents a problem of dominant importance to the Navy. Before the innovation of the resilient isolation mount, the major contributor to the total radiated noise from submarines was vibration transmission from machinery to hull via the foundation. Although the isolation mount, inserted between machinery feet and foundation, largely controlled this noise transmission path, other paths defined by piping, pipe hangers, power-cable bundles, and exhaust stacks were revealed to be potential contributors to the total radiated noise spectrum. The relatively high rigidity of these path elements, particularly those elements constituting the fluid piping path, "short circuit" and degrade the effectiveness of the isolation mounts.

PRIOR WORK

To aid designers in obtaining optimum vibration attenuation and structural reliability characteristics for piping systems, studies were initiated to characterize vibration transmission properties of flexible pipe connections. The flexible connections investigated included the 4-inch diameter Dacron-lined and steel-braided flexible hoses,[1] and the 4-inch diameter Electric Boat (EB) flexible pipe coupling.[2] Comparison of these flexible connections showed that, generally, the 4-inch diameter Dacron-lined hose had greater vibration attenuation than did the steel-braided hose and EB flexible coupling.

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[1]Superscripts refer to similarly numbered entries in the Technical References at the beginning of this report.

OBJECTIVES

One objective of this investigation was to compare the vibration transmission characteristics of several types of 2-1/2-inch diameter flexible connections. Included are the Dacron-lined and steel-braided flexible hoses and EB flexible couplings. Another objective was to study one 3-inch diameter flexible connection, the Dacron-lined hose, and to predict the responses of the 3-inch steel-braided hose and EB flexible couplings based on the measured responses of the 2-1/2- and 4-inch connections.[1,2] The third objective was to present a compendium of results of vibration transmission properties of all flexible connections investigated. It would include not only the vibration properties of the 2-1/2- and 3-inch connections, but also the properties of the 4-inch connections previously reported.[1,2]

INVESTIGATION

Two means of evaluating the vibration transmission properties of the flexible connections were used. One method consisted of measuring the blocked transfer impedances directly, and was used to characterize the 4-inch Dacron-lined and steel-braided hoses.[1] The other method, used in evaluating the 4-inch diameter EB flexible coupling[2] and remaining connections, relied upon determining the blocked transfer impedances and blocked force ratios by analytical-experimental means.

DIRECT MEASUREMENT OF BLOCKED TRANSFER IMPEDANCE

The method of directly measuring the blocked transfer impedances of the 4-inch Dacron-lined and steel-braided hoses has been described in detail.[1] However, it is desirable to give a brief description of the method. Figure 1 shows the arrangement of the flexible hose terminated by a dynamic-force measuring fixture which, in turn, is terminated by a 22,000-pound seismic block, offering a high impedance compared to that of the flexible connection. The terminal numbers assigned to the two interfaces represent the translational and rotational orthogonal axes. A rigorous generalized transfer impedance matrix $[F] = [Z] \cdot [V]$ can be written where $[F]$ consists of a six-element column matrix of translational and rotational forces developed at the blocked output. The matrix $[Z]$ consists of 36 transfer impedance elements, and the six-element column matrix $[V]$ contains the translational and rotational input velocities. Due to the limitation imposed by instrumentation and experimental techniques, the rotational impedance elements of the matrix could not be measured with confidence. These elements were eliminated from the matrix. Also, it was assumed that the blocked forces developed normal to the output interface were larger than the forces developed in the other two directions. The matrix equation was reduced, therefore, to

$$[F_8] = [Z_{81}\ Z_{82}\ Z_{83}] \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \qquad \ldots\ldots(1)$$

where Z_{81}, Z_{82}, and Z_{83} are experimentally measurable blocked transfer impedances. The blocked forces were measured with four EB force gages arranged symmetrically around the periphery of the fixture, Figure 1.

Each of the three impedance elements in the matrix of Equation (1) resulted from a graphical power summation of the sinusoidal blocked force signals from each of the four force gages ratioed to one of the sinusoidal velocity input signals. For example, the magnitude of Z_{81} can be written as

$$Z_{81} = \frac{F_8}{V_1} = \left[\frac{|F_{8(a)}|^2}{|V_1|^2} + \frac{|F_{8(b)}|^2}{|V_1|^2} + \frac{|F_{8(c)}|^2}{|V_1|^2} + \frac{|F_{8(d)}|^2}{|V_1|^2} \right]^{1/2}$$

where subscripts a, b, c, and d refer to the individual force gages. Similar expressions can be written for Z_{82} and Z_{83} by repeating the procedure with velocity inputs applied at the remaining two terminals, 2 and 3. The input velocities were excited by a Goodmans (1-pound force) vibration shaker and were sensed by means of a Clevite 25D21 accelerometer. Velocities were obtained by electronically time integrating the acceleration signals.

The equations describing Z_{81}, Z_{82}, and Z_{83} can be power summed to yield a combined impedance response curve. The result describes the flexible connection when a sinusoidal exciting velocity is applied at an arbitrary angle to the input. The total blocked transfer impedance of the flexible connection can be expressed, therefore, as

$$Z_T = \frac{1}{\sqrt{3}} \left[|Z_{81}|^2 + |Z_{82}|^2 + |Z_{83}|^2 \right]^{1/2} \qquad \ldots\ldots(2)$$

ANALYTICAL-EXPERIMENTAL METHOD

An analytical-experimental approach, based on the work of Smith,[3,4] was used to evaluate the blocked transfer impedance of the 4-inch diameter EB flexible coupling[2] and the remaining flexible connections. Item (a), Figure 2, shows the EB flexible coupling. Item (b), Figure 2, is its schematic representation. The numbered terminals at each interface represent orthogonal coordinate axes at which uncoupled forces and velocities are developed. Uncoupled velocity response equations can be written that will completely define the flexible connections as a function of free driving point and transfer mobilities. These equations are derived in Appendix A. To provide unity velocity excitation to the flexible connection and to simplify solution of the mobility matrix, free driving point mobilities of a mounted trim pump were measured at the outlet flange. Evaluation of the vibration characteristics of the flexible connection necessitated mathematically coupling the uncoupled velocity response equations of pump and flexible connection by proper application of boundary conditions at the pump-flexible connection interface. Blocked termination conditions were imposed upon the flexible connection by assigning zero velocity to the response equations defining the output. The resulting set of linear simultaneous equations were solved for the blocked termination forces and the forces and velocities developed at the flexible connection input interface. Ratioing the computed forces and velocities yielded blocked transfer impedances and blocked force ratios.

It would be impractical to attempt to compare the various sizes and types of hoses and couplings utilizing the nine transfer impedances and nine force ratios computed for each flexible connection. For practical considerations, the nine transfer impedances were reduced to three by a power summation. As an example, one of the three power-summed blocked transfer impedances, Z_7^*, was defined as

$$Z_7^* = \frac{1}{\sqrt{3}}\left[\left|\frac{F_7}{V_4}\right|^2 + \left|\frac{F_7}{V_5}\right|^2 + \left|\frac{F_7}{V_6}\right|^2\right]^{1/2} .$$

Similar expressions were written for Z_8^* and Z_9^*. Power summing the impedances, Z_7^*, Z_8^*, and Z_9^*, yielded a combined transfer impedance defined as

$$Z_T = \left[\left|Z_7^*\right|^2 + \left|Z_8^*\right|^2 + \left|Z_9^*\right|^2\right]^{1/2} \qquad \ldots\ldots(3)$$

A similar need existed to reduce the bulk of the computed force ratios. Each of the three blocked output forces was ratioed to the power sum of the forces developed at the input interface. For example, the force ratio T_8^* involves the blocked forces developed at Terminal 8 divided by the power sum of the input forces and can be expressed as

$$T_8^* = \frac{F_8}{\left[\left|F_4\right|^2 + \left|F_5\right|^2 + \left|F_6\right|^2\right]^{1/2}} .$$

Similar expressions were written for T_7^* and T_9^*. A further reduction of the three force ratios was necessary to define the vibrational characteristics using one expression, i.e., a power summation of the three force ratios T_7^*, T_8^*, and T_9^*. The combined force ratio is defined by

$$T_T^* = \left[\left|T_7^*\right|^2 + \left|T_8^*\right|^2 + \left|T_9^*\right|^2 \right]^{1/2} \quad . \qquad .....(4)$$

This gives an indication of the vibrational amplification or attenuation properties of the flexible connections.

The purpose of this investigation was to compare the vibrational characteristics of the flexible connections rather than to define the noise transmission of the connections when installed in a piping system. It was the opinion, therefore, that a power summation of absolute magnitudes, neglecting phase demands, would be adequate and meaningful. Useful comparative data would be available in terms of one transfer impedance and one force ratio for each flexible connection to aid in future selection of piping system components.

The uncoupled velocity response equations, shown in Appendix A, are functions of the mobilities of the flexible connections when they are free from constraints. Each mobility element in the matrix, Equation (A-4), was experimentally measured by applying sinusoidal excitation at the input terminals, 4, 5, and 6, Figure 2. The three free driving point mobilities, m_{44}, m_{55}, and m_{66}, were measured at Terminals 4, 5, and 6 with a Wilcoxin Model 820 impedance head. The nine remaining free transfer mobilities were measured using the force-measuring element of the impedance head and a Clevite 25D21 accelerometer, each oriented at the proper terminals. The acceleration signals were time-integrated, ratioed with the force signals, and processed by the electronic system, the schematic of which is shown in Figure 3. Digitized mobility magnitudes and phase angles were recorded by the analog to digital instrumentation as were the three driving point mobilities of the trim pump, measured at the output flange. With the collected mobility measurements, Equation (A-4) was solved for the desired blocked forces and input forces and Equation (A-1) for the input velocities.

RANGE OF EXPERIMENTATION

Vibration transmission properties describing the flexible connections were determined for the following conditions:

- Blocked transfer impedances directly measured for the 4-inch diameter Dacron-lined and steel-braided hoses, unfilled and filled with water pressurized to 600 psig.*

- Blocked transfer impedances and force ratios computed for the 4-inch EB flexible coupling, unfilled and filled with water pressurized to 600 psig.

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*Abbreviations used in this text are from the GPO Style Manual, 1967, unless otherwise noted.

- Blocked transfer impedances and force ratios computed for the 2-1/2-inch diameter flexible connections, unfilled and filled with water pressurized to 700 psig. The maximum allowable pressure permitted for the EB flexible coupling limited the pressures applied to the 2-1/2-inch connections to 700 psig.

- Blocked transfer impedances and force ratios computed for the 3-inch diameter Dacron-lined hose, unfilled and water filled at 900 psig.

RESULTS

Figures 4 through 9 are the combined blocked transfer impedances and force ratios of the pressurized flexible connections. Each of Figures 4, 5, and 8 compares vibration responses of connections of comparable size.

Figures 6 and 9 are responses of the 3-inch diameter Dacron-lined hose, and Figure 7 is the force ratio response of the 4-inch EB flexible coupling. The first report[1] did not include measurements of force ratios of the 4-inch diameter flexible hoses. In this report emphasis is placed upon the combined vibration characteristics, Z_T^* and T_T^*, rather than those responses involving the individual output terminals. Figure 10 presents the transfer impedances, Z_T^*, of the three unpressurized Dacron-lined flexible hoses of 2-1/2, 3, and 4-inch diameter. From the comparison of these impedances, an attempt was made to predict the responses of the 3-inch diameter steel-braided hose and EB flexible coupling. Figures 11 through 17 show the transfer impedance characteristics of the flexible connections as functions of the pressure loading.

RESPONSE COMPARISONS

Figure 4 compares the 4-inch-diameter flexible couplings, pressurized to 600 psig, and shows that the hoses provide less vibration transmission than does the EB coupling configuration. Of greatest importance is the transmission difference between the EB coupling and Dacron-lined hose, particularly between 150 and 400 hertz. The minimum magnitude of impedance in this region is approximately 35 db below that of the EB coupling. The transmission characteristics of the Dacron-lined and steel-braided hoses are comparable over the frequency range except between 150 and 400 Hz and at 550 Hz where the Dacron-lined hose exhibits lower vibration transmission.

Evaluations of the 2-1/2-inch-diameter connections are shown in Figures 5 and 8, pressurized to 700 psig. Similar characteristics result for these connections above 120 Hz as for the 4-inch size, i. e., the EB flexible coupling generally exhibited higher vibration transmission than either the Dacron-lined or steel-braided hoses.

Comparing the two connections indicated that the steel-braided hose transmits less vibration than does the Dacron-lined hose, from 20 to 120 Hz; however, above 120 Hz, an opposite relationship exists, i. e., the Dacron-lined hose transmits less vibration than does the steel-braided hose. As an example, the blocked transfer impedance of the Dacron-lined hose at 250, 400, and 1000 Hz is approximately 35 db lower than that of the steel-braided hose. The force ratios, T_T^*, Figure 8, shows that the Dacron-lined hose and EB flexible couplings offer comparable attenuation from 20 to about 180 hertz. Above 180 Hz, however, attenuation by the Dacron-lined hose exceeds that of the other two flexible connections by approximately 25 to 30 db between 250 and 420 hertz.

Figures 6 and 9, the blocked transfer impedance and force ratio of the pressurized 3-inch-diameter Dacron hose, shows the low impedance and high attenuation region between 180 and 520 Hz, characteristic of Dacron-lined hoses.

Comparing the blocked transfer impedances of the three sizes of unpressurized Dacron-lined hoses, shown in Figure 10, indicated that the 3-inch hose does not clearly lie between the response magnitudes of the 4-and 2-1/2-inch Dacron hose. Similar shapes and magnitudes, however, characterize the responses of the three connections. It is reasonable to expect, therefore, that similar relationships will exist between the three sizes of steel-braided hoses and flexible couplings.

PRESSURE EFFECT

The most notable effects of pressurizing the flexible connections are reflected in the blocked transfer impedances of the Dacron-lined hoses, Figures 11, 14, and 15. An increase of 20 to 30 db in impedance magnitudes is shown for the 2-1/2-inch hose between 150 and 400 Hz and above 2000 hertz. The 3-inch Dacron-lined hose shows an increase of about 20 db between 100 and 800 Hz, above which little difference is noticed between the pressurized and unpressurized condition. Generally, the remaining flexible connections, the steel-braided hose and EB flexible couplings, are relatively independent of pressure from 20 to 300 hertz. Above 300 Hz, however, a dependency upon pressure is noted. This is an apparent characteristic of the EB flexible couplings, Figures 13 and 17.

DISCUSSION

A brief discussion of the limitations of the results of this investigation is necessary at this point. A flexible connection is normally terminated by a piping system which is often already quite flexible. Since it is the termination conditions that greatly influence the effectiveness of an isolation element, the vibration response of the piping to which the flexible connection is attached must be known. Only then will it be possible to describe, accurately, the transmission characteristics of the flexible hose or coupling. The blocked transfer impedance method for evaluating isolation devices yields meaningful results only if the isolation device would normally be terminated by a rigid structure in an actual shipboard machinery system. A resilient mount terminated by a rigid foundation is an example of an isolation device realistically defined by a blocked transfer impedance measurement. It must be understood, therefore, that the blocked transfer impedance method used in these investigations offers a valuable criterion only when used to compare different types and sizes of flexible couplings and hoses.

LIMITATION OF RESULTS

The usefulness of the response characteristics is limited by the analysis and measurement techniques employed.

The use of power summation, while convenient for quantitative comparisons, ignores phase coherence and yields magnitudes of impedance or force ratios equal to or greater than the largest individual magnitudes being summed. Power summing, therefore, tends to reinforce modal coupling and may not realistically describe the dynamic force profile of the flexible connection at its termination.

Pressurizing the flexible connections required use of blank flanges to terminate the ends of the flexible hoses and couplings. The measured data, therefore, became partially a function of the physical constraint imposed upon the pressurized fluid column. Transfer impedance and force ratio responses would show a greater stiffening effect due to the blank flange, particularly along the longitudinal axes designated by Terminal 7, Item (b), Figure 2, than would result if the flexible connection were connected into a shipboard pressurized piping system. The combined transfer impedances, Z_T^*, and combined force ratios, T_T^*, are predominantly affected by the exaggerated pressure sensitivity of the individual transfer impedances, Z_7^* and force ratios, T_7^*.

SIMILARITY OF RESPONSES

A remarkable similarity exists between the blocked transfer impedances of the three sizes of unpressurized Dacron-lined hoses, Figure 10. This quality makes possible easy categorization of flexible connections as an aid to designers attempting to quantify the contribution of these isolation devices as vibration transmission paths.

It is also feasible that one representative value describing the transmission characteristics of different sizes of each type of flexible connection could be used in current surface ship and submarine machinery noise prediction methods.[5] This method relies predominantly upon quantitative representation of vibration characteristics of machinery items and their numerous transmission paths to the water. However, as the flexible connection transmission properties are based on blocked termination conditions, use of these characteristics for the prediction method must be tempered according to the philosophy discussed above.

CONCLUSIONS

Based on blocked transfer impedance and force ratios of the 2 1/2- and 4-inch-diameter flexible connections, the following conclusions are drawn:

- The Dacron-lined hose generally exhibits lower vibration transmission properties than does the steel-braided hose and EB flexible couplings.

- The magnitudes of the unpressurized blocked transfer impedance of the 3-inch Dacron-lined hose are comparable to those of the unpressurized 2 1/2- and 4-inch Dacron hoses. It is concluded, therefore, that a similar prediction can be made concerning the responses of the 3-inch steel-braided hose and 3-inch EB flexible couplings.

- Between 20 and approximately 800 Hz, the Dacron-lined hoses generally show greater pressure sensitivity than the steel-braided hoses and EB flexible couplings. Above 800 Hz, all the connections show comparative sensitivity.

FUTURE PLANS

Further investigations of the vibration transmission characteristics of flexible hoses and couplings are not considered necessary. However, a compiling of shipyard design procedures for effective machinery noise reduction in the form of "do's and don'ts," will be promulgated. The compilation will supplement existing noise reduction guide lines and will include proper use and suspension of flexible connections to minimize their performance as noise transmission paths.

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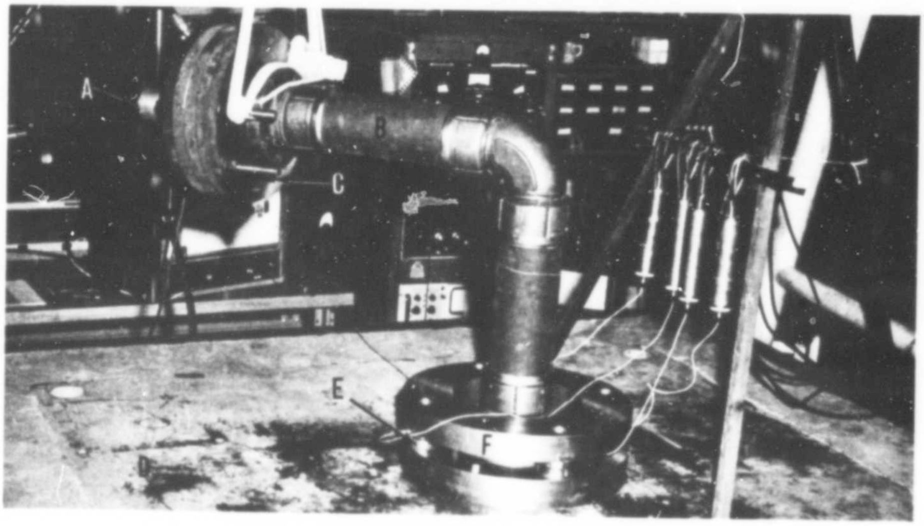
Item (a)

Ⓐ Goodmans Vibration Exciter
Ⓑ Flexible Hose
Ⓒ High Impedance Constraint
Ⓓ Seismic Block
Ⓔ Force Gages
Ⓕ Force Gage Fixture



Item (b)

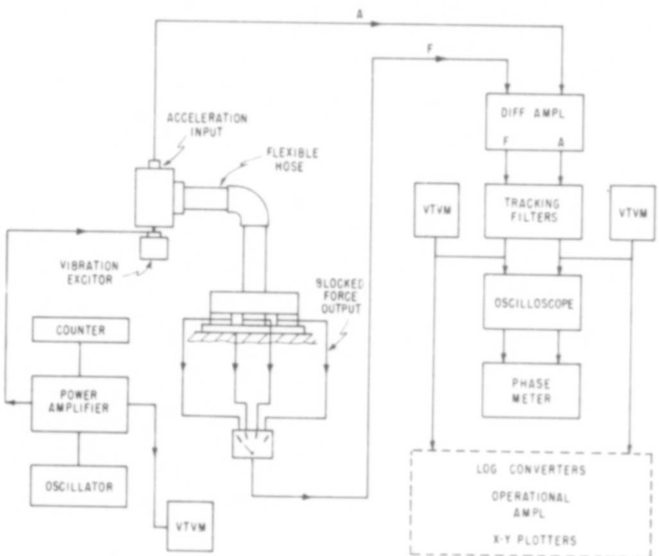


Figure 1
Experimental Measurement Blocked Transfer Impedance

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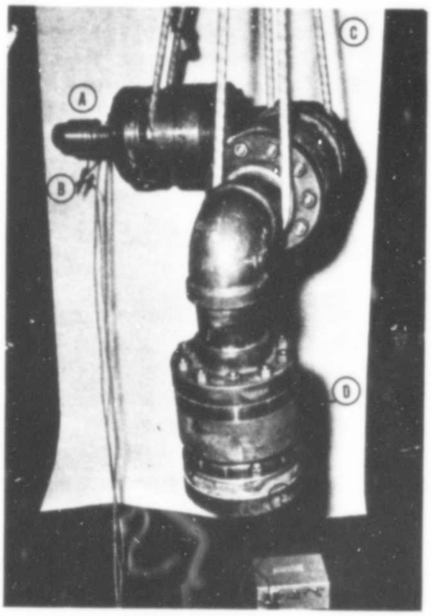
Item (a)

Ⓐ Goodmans Vibration Exciter
Ⓑ Impedance Head
Ⓒ Suspension Cord
Ⓓ EB Flexible Coupling (3-Planar Configuration)
Ⓔ Accelerometers (Orthogonally Oriented)



Item (b)

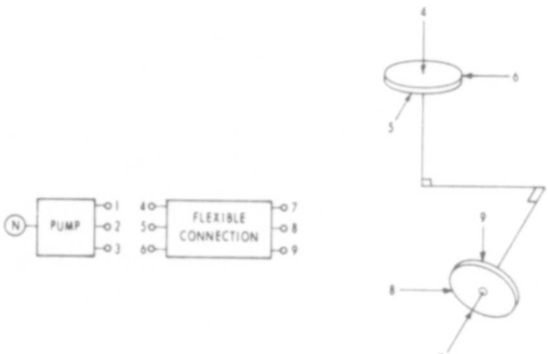


Figure 2
EB Flexible Couplings (3-Planar Configuration), Freely Suspended

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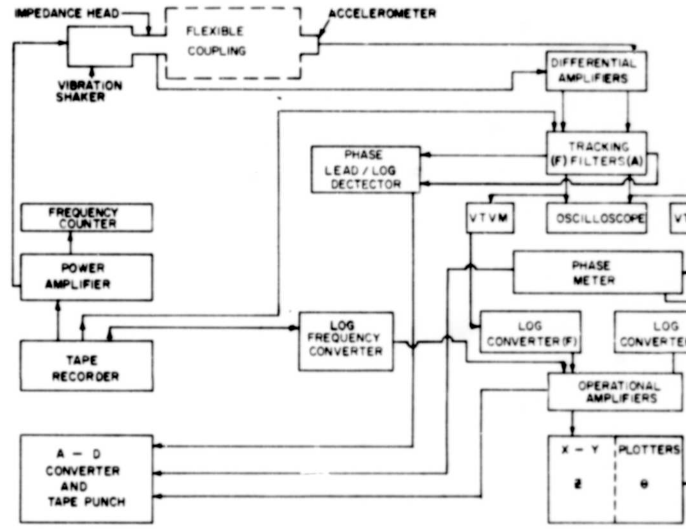

Figure 3
Instrumentation System

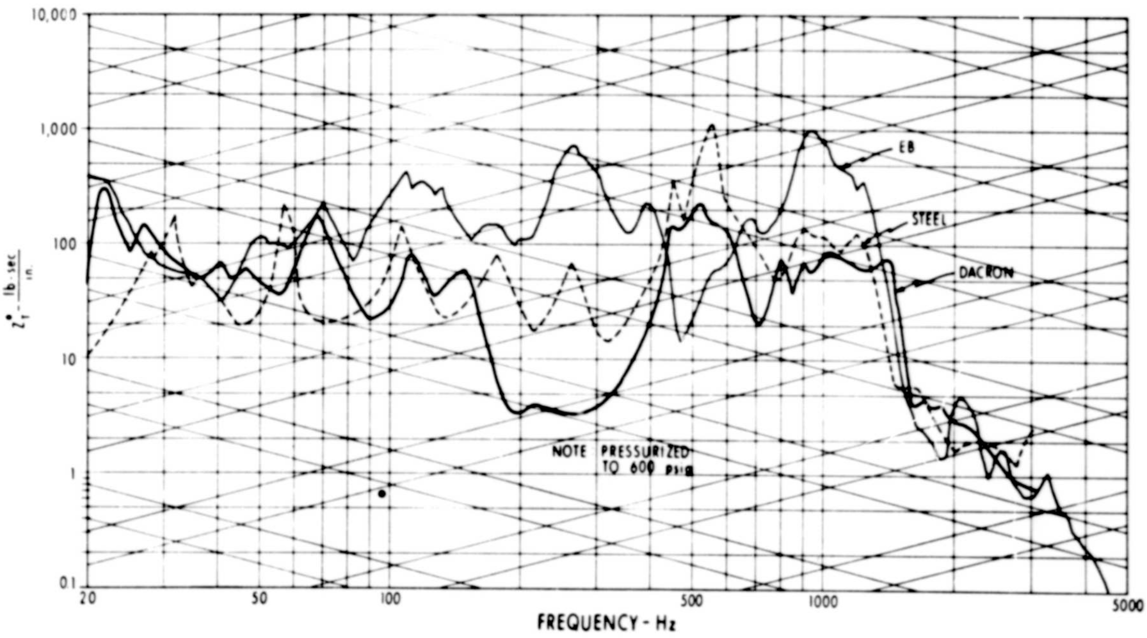

Figure 4
Combined Blocked Transfer Impedance of 4-Inch Flexible Connections, Z^*_T

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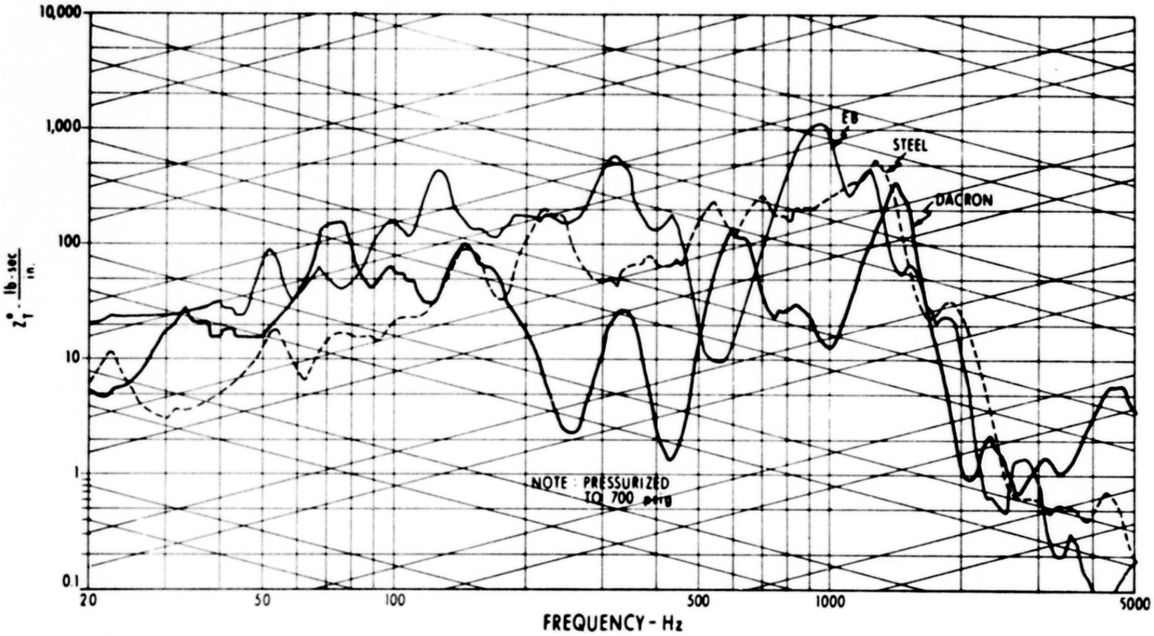

Figure 5
Combined Blocked Transfer Impedance of 2-1/2-Inch Flexible Connection, Z_T^*

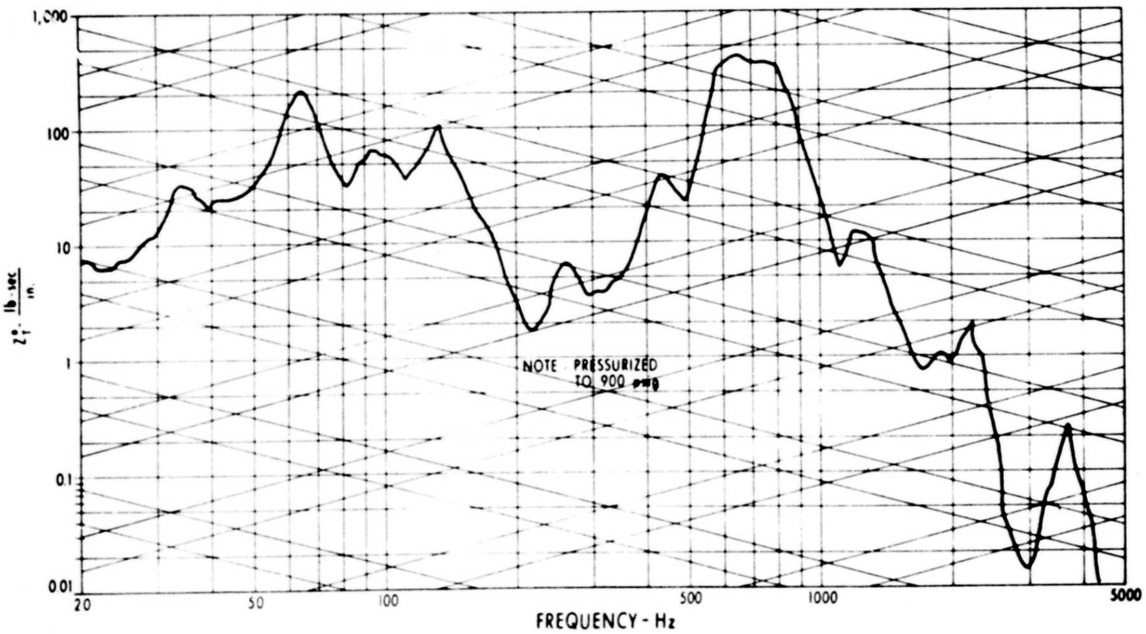

Figure 6
Combined Blocked Transfer Impedance of 3-Inch Dacron-Lined Flexible Hose, Z_T^*

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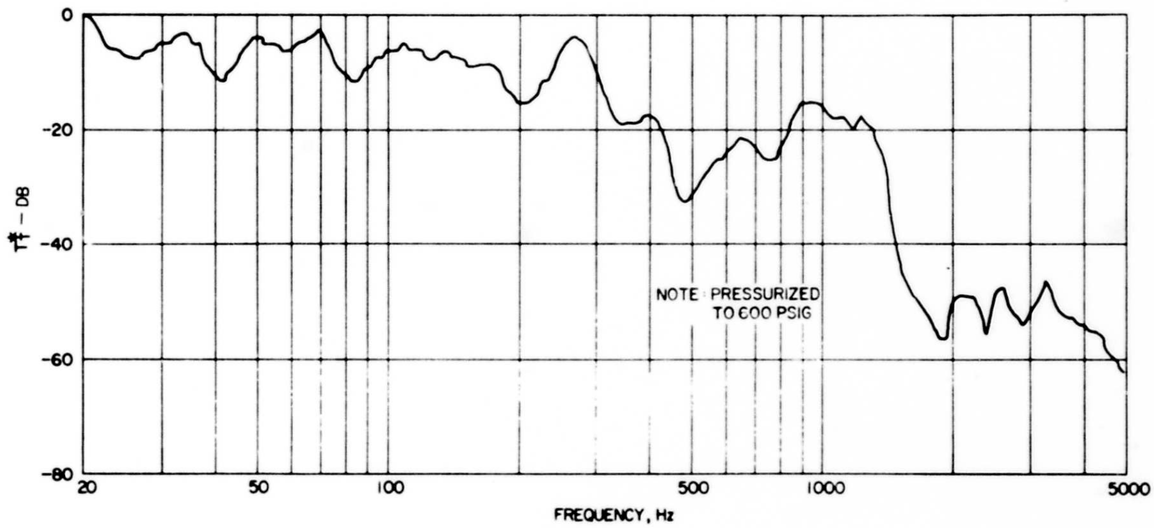

Figure 7
Combined Blocked Force Ratio of 4-Inch EB Flexible Couplings, T^*_T

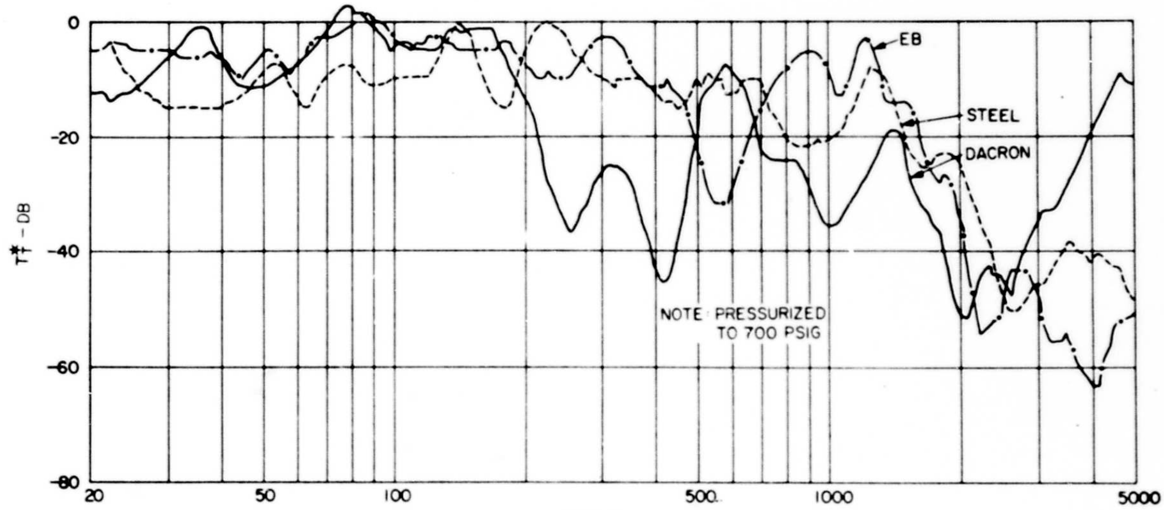

Figure 8
Combined Blocked Force Ratios of 2-1/2-Inch Flexible Connections, T^*_T

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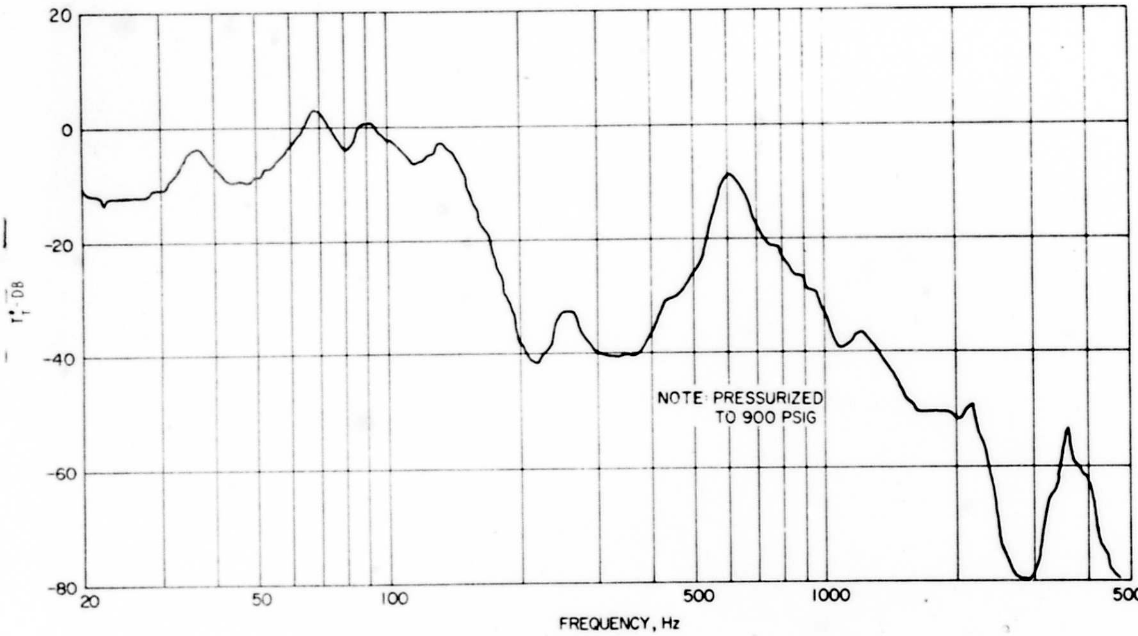

Figure 9
Combined Blocked Force Ratio of 3-Inch Dacron-Lined Flexible Hose, T_T^*

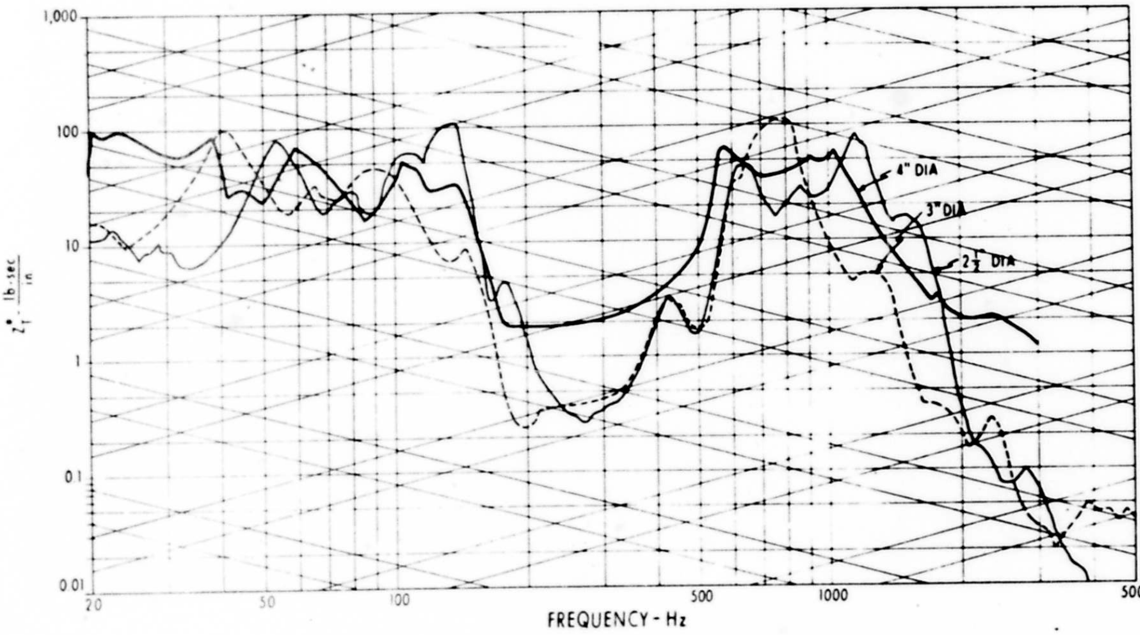

Figure 10
Combined Blocked Transfer Impedances of Three Sizes of Flexible Connections, Z_T^*

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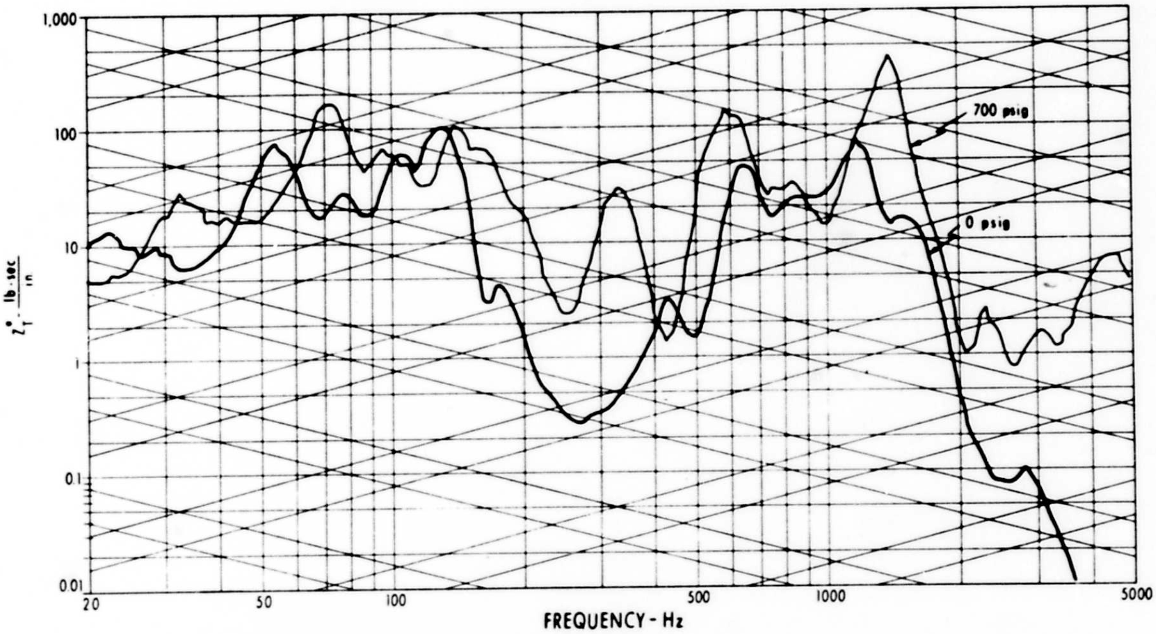

Figure 11
Combined Blocked Transfer Impedances of Pressurized and Unpressurized 2-1/2-Inch Steel-Braided Hose, Z_T^*

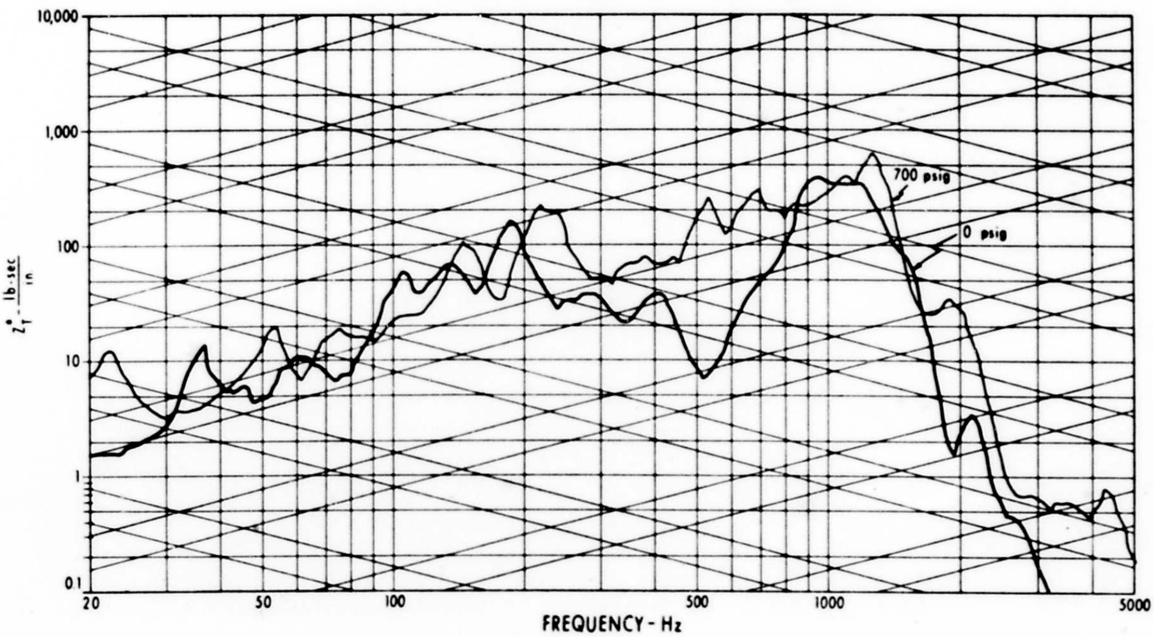

Figure 12
Combined Blocked Transfer Impedances of Pressurized and Unpressurized 2-1/2-Inch Steel-Braided Hose, Z_T^*

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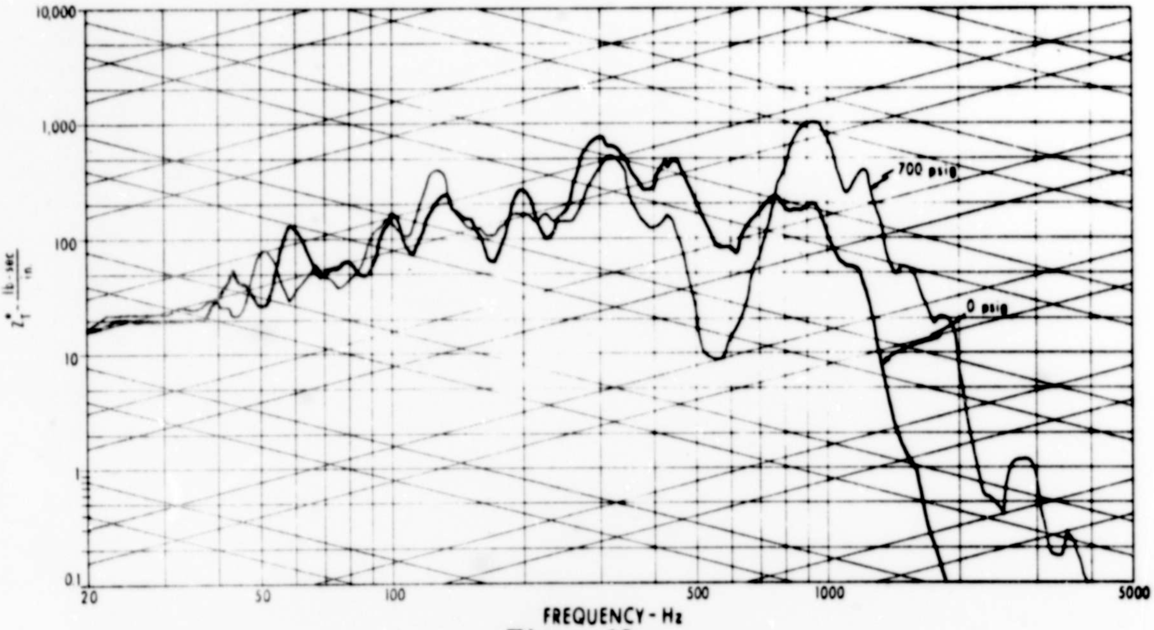

Figure 13
Combined Blocked Transfer Impedances of Pressurized and Unpressurized 2-1/2-Inch EB Flexible Coupling, Z_T^*

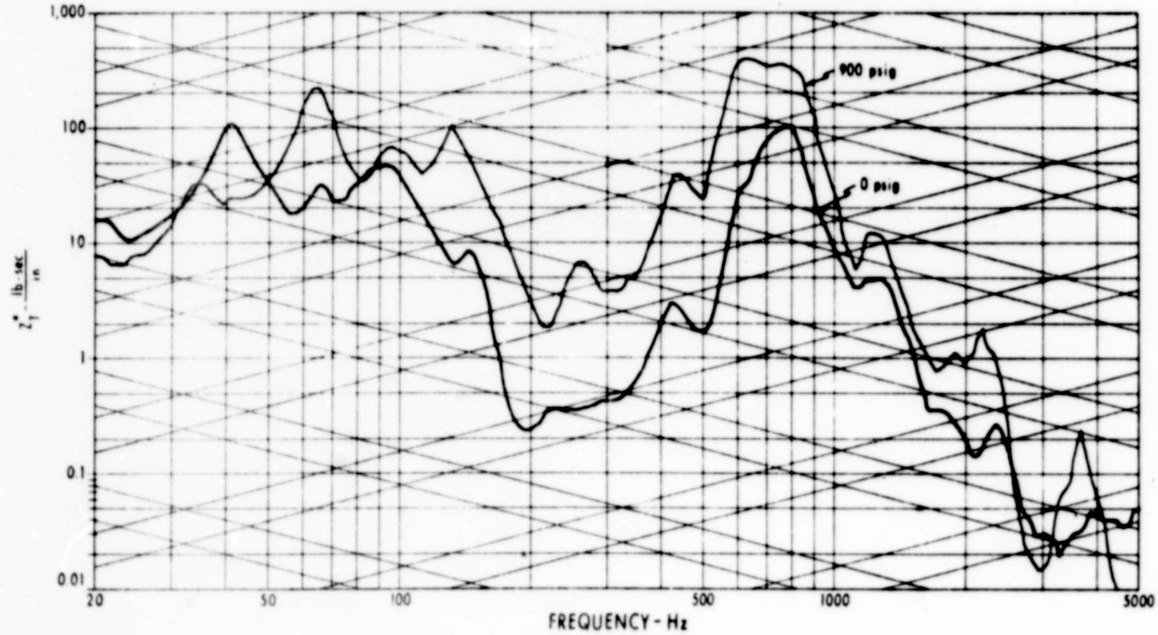

Figure 14
Combined Blocked Transfer Impedances of Pressurized and Unpressurized 2-1/2-Inch EB Flexible Coupling, Z_T^*

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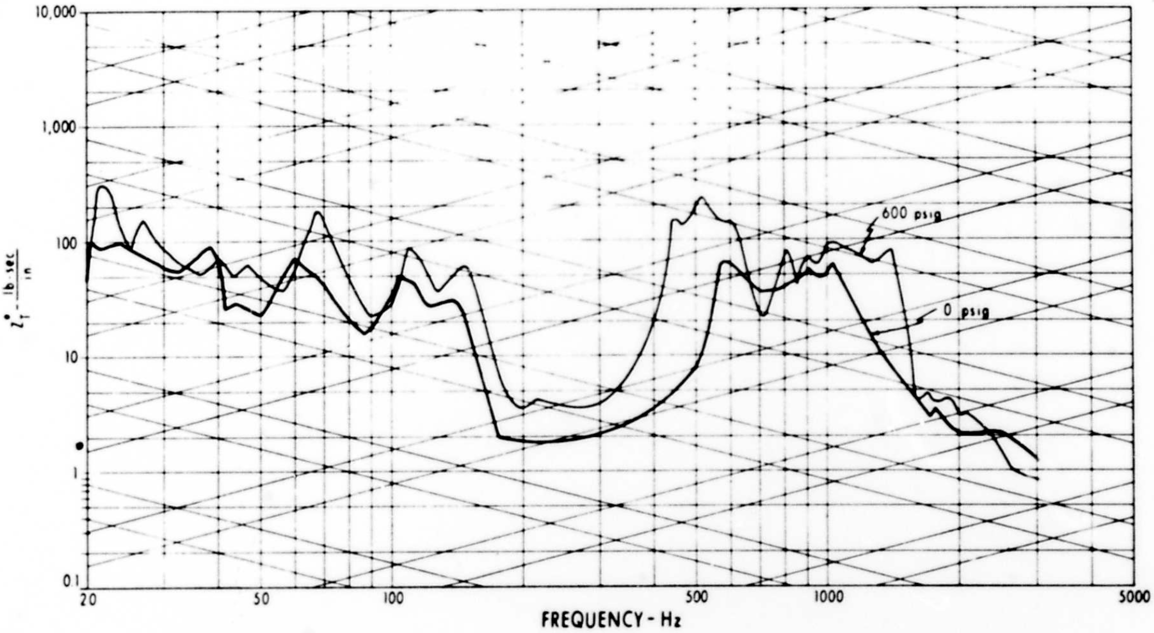

Figure 15
Combined Blocked Transfer Impedances of Pressurized and Unpressurized 2-1/2-Inch EB Flexible Couplings, Z_T^*

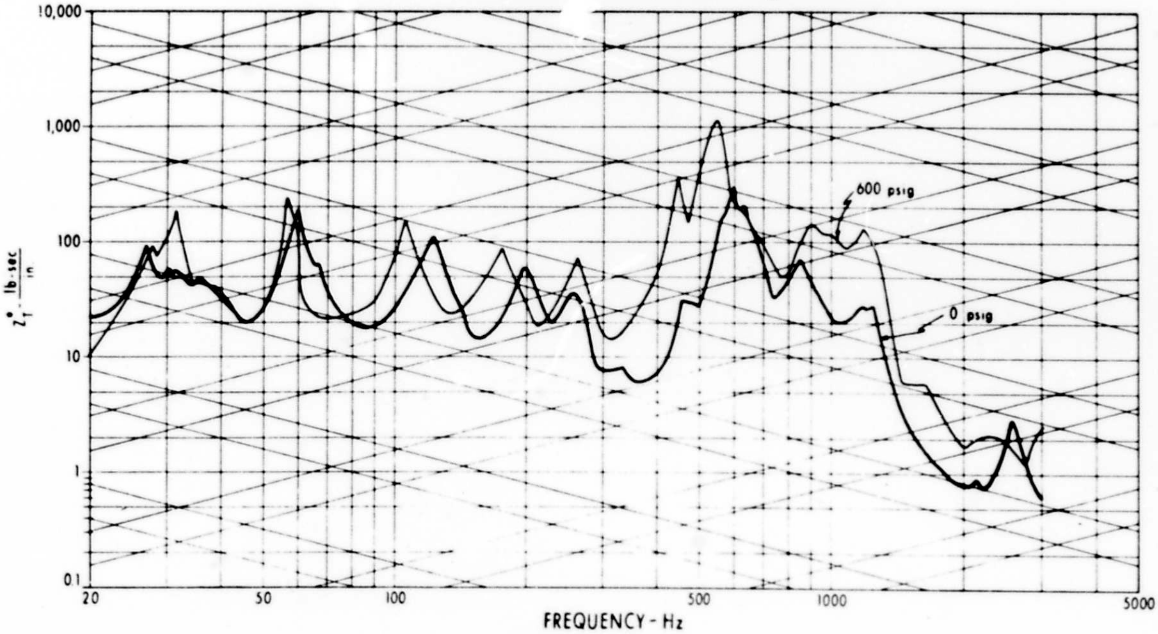

Figure 16
Combined Blocked Transfer Impedances of Pressurized and Unpressurized 4-Inch Dacron-Lined Hose, Z_T^*

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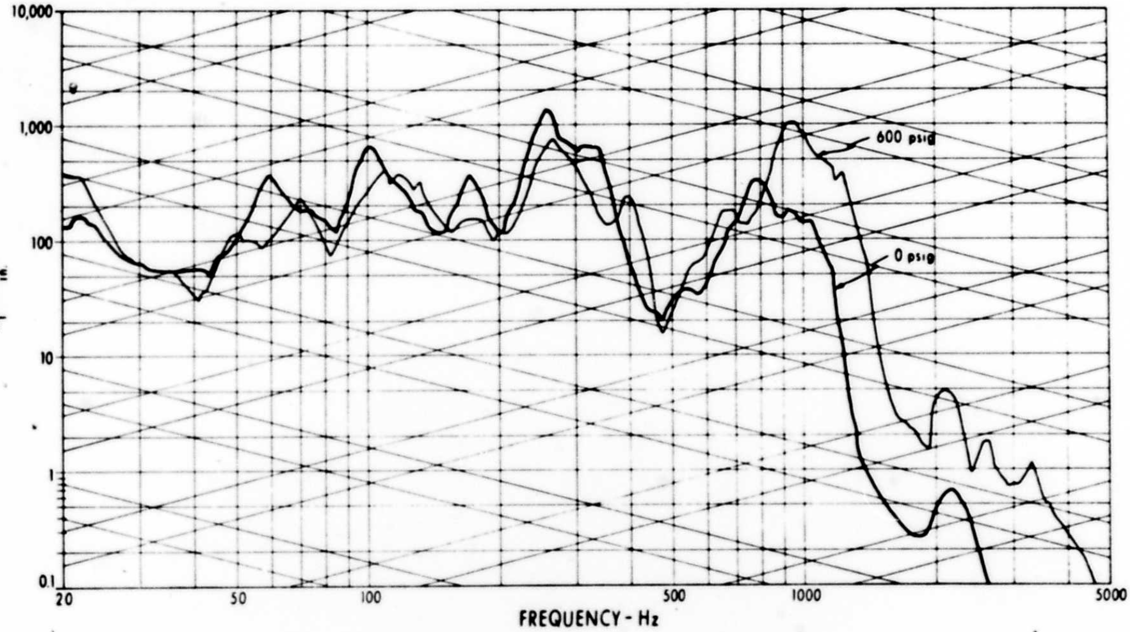

Figure 17
Combined Blocked Transfer Impedances of Pressurized and Unpressurized 4-Inch EB Flexible Couplings, Z_T^*

Appendix A

Development of Blocked Transfer Impedance and Force Ratio Equations

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The uncoupled velocity response equations of the freely suspended flexible connection are a function of the uncoupled forces at each numbered terminal and the experimentally measured free driving point and transfer mobilities of the connection. The response equations describing the suspended connection in Figure 2 of the text can be written as follows:

Flexible Connection at Input Interface

$$\begin{aligned} v_4 &= f_4 m_{44} + f_5 m_{45} + f_6 m_{46} + f_7 m_{47} + f_8 m_{48} + f_9 m_{49} \\ v_5 &= f_4 m_{54} + f_5 m_{55} + f_6 m_{56} + f_7 m_{57} + f_8 m_{58} + f_9 m_{59} \\ v_6 &= f_4 m_{64} + f_5 m_{65} + f_6 m_{66} + f_7 m_{67} + f_8 m_{68} + f_9 m_{69} \end{aligned} \quad \text{.....(A-1)}$$

Flexible Connection at Output Interface

$$\begin{aligned} v_7 &= f_4 m_{74} + f_5 m_{75} + f_6 m_{76} + f_7 m_{77} + f_8 m_{78} + f_9 m_{79} \\ v_8 &= f_4 m_{84} + f_5 m_{85} + f_6 m_{86} + f_7 m_{87} + f_8 m_{88} + f_9 m_{89} \\ v_9 &= f_4 m_{94} + f_5 m_{95} + f_6 m_{96} + f_7 m_{97} + f_8 m_{98} + f_9 m_{99} \end{aligned} \quad \text{.....(A-2)}$$

To facilitate solution of the above equations when the proper termination boundary conditions are applied to Equation (A-2), a set of "dummy" response equations were used to simulate the boundary conditions applied to the flexible connection input when attached to a trim pump. The equations involved the mobility measurements of a mounted trim pump at the discharge flange, and are as follows:

$$\begin{aligned} v_1 &= f_1 m_{11} + v_{01} \\ v_2 &= f_2 m_{22} + v_{02} \\ v_3 &= f_3 m_{33} + v_{03} \end{aligned} \quad \text{.....(A-3)}$$

The v_0's are the free velocities that exist at the pump output flange when it is free of connections. They represent the source of velocity excitation by the pump on the flexible connection and for convenience, each is assigned a value of unity.

To unite pump and flexible connection, the following equalities were applied to Equations (A-1) and (A-3):

$$v_1 = v_4 \qquad f_1 + f_4 = 0$$

$$v_2 = v_5 \qquad f_2 + f_5 = 0$$

$$v_3 = v_6 \qquad f_3 + f_6 = 0$$

Applying the conditions that $v_7 = v_8 = v_9 = 0$ to Equation (A-2), simulated a blocked termination. The matrix form of this system of linear equations can be written as $[V] = [M]\ [F]$ or in expanded form

$$\begin{bmatrix} 1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} m_{44}+m_{11} & m_{45} & m_{46} & m_{47} & m_{48} & m_{49} \\ m_{54} & m_{55}+m_{22} & m_{56} & m_{57} & m_{58} & m_{59} \\ m_{64} & m_{65} & m_{66}+m_{33} & m_{67} & m_{68} & m_{69} \\ m_{74} & m_{75} & m_{76} & m_{77} & m_{78} & m_{79} \\ m_{84} & m_{85} & m_{86} & m_{87} & m_{88} & m_{89} \\ m_{94} & m_{95} & m_{96} & m_{97} & m_{98} & m_{99} \end{bmatrix} \times \begin{bmatrix} f_4 \\ f_5 \\ f_6 \\ f_7 \\ f_8 \\ f_9 \end{bmatrix}$$

The experimentally measured mobility magnitudes and associated phase angles were sampled and recorded from 20 to 5000 Hz, in 174 equally spaced increments, by the instrumentation shown in Figure 3 of the text. To reduce the amount of measured mobilities to a less formidable number, reciprocity and symmetry was applied. A total of 12 mobilities were required, therefore, to describe the translational responses of each flexible connection.

Solution of the matrix equation yielded the coupled forces developed at the flexible connection input, f_4, f_5, and f_6 and the blocked forces at the flexible connection termination, f_7, f_8, and f_9. Insertion of the computed forces into Equation (A-1), evaluated the developed coupled velocities at the flexible connection input, v_4, v_5, and v_6. The computed forces and velocities were ratioed in accordance with the equations presented in "Analytical-Experimental Method" of the text, for each of the 174 frequency increments from 20 to 5000 hertz.

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13. ABSTRACT

The results of studies of vibration transmission on three sizes of pressurized and unpressurized flexible pipe connections are presented. The connections include Dacron-lined and steel-braided hoses in "dog-leg" configurations and Electric Boat flexible pipe couplings in three-planar configurations. Results showed that, generally, the Dacron-lined hoses exhibited lower vibration transmission characteristics than did the steel-braided hoses and Electric Boat flexible couplings. However, the Dacron-lined hoses showed a larger increase in vibration transmission between 20 and 800 hertz when pressurized, than did the other types of flexible connections in the same frequency range. Results also showed that little difference existed between the magnitudes of transfer impedance for the three sizes of unpressurized Dacron-lined flexible hose.

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