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EFFECTIVE MASS AND DAMPING OF SUBMERGED STRUCTURES

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SUMMARY

A number of structures important for safety in nuclear power plants are submerged in water. These include spent fuel storage racks, main pressure relief valve lines, and internal structures in the reactor vessel. Dynamic analyses of such structures must include the force and damping effects of water. A wide variety of modeling assumptions are being used in design analyses, and currently there are no uniform positions by which to judge the adequacy of the assumptions. A study was carried out to establish a technical basis for evaluating the assumptions and to recommend suitable methods to describe the effects of the water.

The results of the study were based on information published in the literature or conveyed by industrial firms. A survey of 32 firms and 49 technical references was carried out. Heavy emphasis was placed on validating the results with available experimental data. The information collected apply generally to idealized structures such as single isolated members, arrays of members, and coaxial cylinders. The results of the study are categorized with respect to such idealized structures, and the applicability to actual reactor structures was discussed through observations and recommendations

The dimensions and fundamental frequencies of nuclear structures of concern were reviewed to indicate the ranges of interest. Most of the experimental data apply to frequencies of the same order as those of nuclear power structures; however, the test specimens were generally much smaller than actual structures. Structural size was found to have an important influence on the added damping due to water. Consequently, a procedure was developed to extrapolate the experimental damping values to structural sizes of concern. Through this procedure the added damping due to water was found generally low for actual structures, if the structures were treated as single isolated members. The damping ranged from $\leq$0.55% for BWR fuel bundles to $\leq$0.29% for 12.0 in. diameter main stream relief valve lines.

The various levels of sophistication in hydrodynamic theories exist; the simplest is potential theory, where incompressible inviscid behavior is assumed. The theory agreed well with experimental added mass data for single isolated members of varying geometries, and the range of applicability was determined to cover the response range expected for seismic design analysis.

The overall conclusion for single isolated members is that the added mass and damping concept is adequate for seismic design analysis. Potential theory can be used to determine the added mass values, and damping can be assumed small but dependent on structural size.

For multiple members such as arrays, members near a wall, and coaxial cylinders, the general conclusion is that potential theory applies for nonflexible members. The added mass is described by a matrix of coefficients. If the members are flexible, theories of higher sophistication become necessary. Insufficient data was available to draw meaningful conclusions concerning damping for multiple members.

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1. Introduction

A number of nuclear power plant structures, such as spent-fuel storage racks, main pressure-relief valve lines, and internals of the reactor vessel, are submerged in water. For seismic analysis of these structures, the effect of the water in terms of forces and damping must be considered. A wide variety of modeling assumptions are being used in design analysis, and, at present, there are no uniform positions by which to judge the adequacy of the assumptions. A study funded by the U.S. Nuclear Regulatory Commission (NRC) was carried out to provide a technical basis for evaluating the assumptions, and to recommend suitable methods to account for the effect of the water. Reference [1] is a detailed final report for the study. This paper summarizes some of the key points of the report.

The methods investigated include the added mass and added damping concept, current design methods, and methods under development. Experimental results available in the literature form the basis of our evaluation whenever possible. We focus on two groups of idealized structures: single isolated members and multiple members. The second group includes two parallel cylinders, members near a boundary, an array of members, and coaxial cylinders. We relate our findings to spent-fuel storage racks, main pressure-relief valve lines, and the internals of the reactor vessel through observations and recommendations. Development of new methods and performing rigorous analyses were not major endeavors for the study.

An extensive survey of the literature and industrial firms was carried out. Forty-nine references were reviewed, and thirty-two industrial firms were contacted. A complete listing of references and firms is given in Ref. [1]. The study revealed that the design methods in current use are quite varied and that, in some instances, rather sophisticated developments are taking place. A tabulation of design methods and an assessment of each in terms of applicability to nuclear power plant structures are given in Ref. [1].

Of special interest to NRC is a recommendation for added mass and damping values made by Newmark and Rosenblueth [2]. This recommendation forms the baseline for NRC's current position on the subject. In Ref. [1] we compared this recommendation with the theoretical and experimental results reviewed.

The fluid-structure interaction for multiple members is significantly more complex than for single isolated members and is less well understood. Consequently, we find it advantageous to separate single isolated members from multiple members in our presentation.

2. Structures and Excitations of Concern

The nuclear power-plant structures and excitations of concern are shown in Table 1. For this study, seismic loads are considered described by the response spectrum in the NRC's Regulatory Guide 1.60 [3]. The structures of concern vary in dimension and arrangement depending on the design and the plant. A representative list of dimensions and/or natural frequencies are given in Table 1.

3. Single Isolated Members

3.1 Added Mass for Single Isolated Members

If a single isolated member is accelerated in a stationary fluid, its acceleration induces the fluid in its immediate neighborhood to accelerate. The accelerating fluid in return induces an added mass effect onto the member. Under sufficiently small amplitudes of motion, cyclic or unidirectional, the added mass phenomenon can be described in terms of an added mass coefficient C_m defined as

$$C_m = \frac{\text{added mass of fluid}}{\text{reference fluid mass}} ,$$

where the reference fluid mass is that of the cylinder of fluid of diameter equal to the dimension perpendicular to the direction of motion, or, in some cases, it is the mass of the displaced fluid. The added mass phenomenon for single isolated members has been rather extensively investigated experimentally and analytically. Theoretical treatment has been quite successful using a simple, incompressible, inviscid theory sometimes referred to as potential theory.

Experimental data for single isolated members are available in Refs. [4 through 12]. Theoretical values of added mass coefficients for a wide range of specimen geometries based on potential theory are tabulated in Refs. [13 and 14]. In Ref. [1] theoretical values are compared with experimental results for nine specimen geometries. The comparison was quite good. Therefore, we take the position that the added mass given by potential theory is valid.

3.2 Added Damping for Single Isolated Members

The damping force acting on a submerged member is usually relatively small and not included in analysis as an acting force. Instead, the effect is usually described as an equivalent viscous damping. The contributions to added damping are:

- Fluid viscosity.
- Component impact.
- Wave generation.
- Acoustic generation.

The last two are forms of radiation damping; i.e., wave or acoustic energy generated radiate away from the submerged member. Reasons are given in Ref. [1] to ignore radiation damping for the nuclear plant structures of concern. Component impact may be a significant source of damping for multiple members, and this will be discussed further when we address multiple members later in this report; however, it is not a source of damping for single isolated members. Therefore, for single isolated members, fluid viscosity is the only source of damping in need of consideration. The results of our study on added damping are based on available test data.

Experimental data on added damping are presented in Refs. [4, 5, 11, and 15] covering a variety of specimen shapes and experimental conditions. The most extensive set of data is found in Ref. [11] where circular cylinders of 0.31-, 0.5-, 0.75-, and 1.0-in. diameters are investigated over the frequencies 2.5 to 18.6 Hz and amplitude-to-diameter (A/D) ratios of up to 2.0. The data of Ref. [11] indicate that added damping can be described by viscous damping up to an A/D value of 0.32 for the smallest specimen (0.31 in. diam) and 0.5 for the largest (1.0 in. diam). Beyond the viscous damping range is the nonlinear range where the damping force becomes proportional to the square of the velocity. The change from linear to nonlinear behavior with increasing A/D value was quite distinct as revealed by test data presented in Ref. [11]. Nonlinear damping was seen to be greater than linear damping, so that using the linear damping value as an approximation in the nonlinear range will be conservative.

3.3 Effect of Structural Size on Added Damping for Single Isolated Members

A decrease in added damping with increasing structural size was found as indicated in Fig. 1. This was confirmed by comparing with a similar trend established for damping of water sloshing in pools. The latter trend is well established, and expressions for the dependence of damping on pool size are given in Refs. [16, 17, and 18]. Several different expressions are seen in these references; however, they all have a common form of,

$$\log (\delta) = \log (A)-(q) \log (R) ,$$

where δ is the damping of the water sloshing in the pool, A is a constant, q is the constant defining the dependence on the pool size, and R is the length of the pool. Depending on the expression used, the value of q ranged from 0.75 to 1.0. To see if the decrease in added damping for submerged single isolated members follows the trend established for water sloshing in pools, the data from Refs. [4, 5, 11, and 15] are plotted in Fig. 1 in terms of log (damping) vs log (specimen size). The scatter is rather wide; however, the decreasing trend is apparent. A straight line was least-square fitted to the data as shown. The slope of this line gave q = 0.85. Because the value of 0.85 fell between the values of 0.75 and 1.0 established for pools, we interpret this as good confirmation that added damping for submerged single isolated members decreases with increasing structural size and that the dependence on structural size is reasonably characterized by Fig. 1. We, then, used Fig. 1 to extrapolate the added damping values for the structural sizes of concern, and the results are tabulated in Table 1. Except for single isolated fuel elements, the damping for all other single isolated members of the structures is quite low. These low values are in agreement with Newmark and Rosenblueth's statement [2] that "damping due to liquid viscosity may be disregarded" for single isolated members of common structural sizes. A detailed discussion of this study on size effect is given in Ref. [39].

3.4 Range of Applicability of the Added Mass and Added Damping Concept for Single Isolated Members

The range of applicability of the added mass and added damping concept for single isolated members can be considered as being defined by the smaller of either the range for added mass or the range for added damping. In Section 3.2 of this paper, the range of applicability of added linear damping was found to vary from an amplitude to diameter (A/D) ratio of 0.32 for a 0.31-in. diameter specimen to an A/D value of 0.5 for a 1.0-in. diameter specimen. The applicable range increases with specimen size, so that we sould expect the range to be greater than an A/D value of 0.5 for specimen diameters larger than 1.0 in. Also in Section 3.2, we observed that beyond the range of applicability for linear damping, the damping increases. Therefore, using linear damping beyond the linear range would be conservative. Consequently, depending on the degree of conservatism desired, linear added damping may be used to some degree beyond its applicability range. Again in Section 3.2 of this paper, the added damping values for single isolated members of structural sizes of actual concern are generally quite low. (See Table 1). Except for the single isolated fuel element, we may choose to ignore the added damping. In this case, the range of applicability for the added damping concept may be disregarded.

Turning now to the range of applicability of the added mass concept for single isolated members, experimental results for added mass coefficient C_m over a wide range of amplitudes for various specimen geometries are presented in Refs. [7] and [12]. In Ref. [1] we used the data to establish the range of applicability by comparing with potential theory. As the amplitude to diameter ratio A/D increases, the test data increasingly deviates from theoretical value. A ± 10% deviation from theoretical value was taken as defining the A/D range of applicability. The results for added mass are tabulated in Table 2. The A/D values for the applicable range of linear damping are also indicated.

The four values of A/D in Table 2 for the applicable range of the added mass concept are in good agreement. The A/D value for a sphere is expected to be higher than that for a cylinder or plate, because it is a finite length specimen (more streamlined), and, therefore, potential flow can be expected to apply over higher values of displacements. The A/D range of 0.32 to 0.5 for the applicability of linear damping is not drastically different from the 0.8 and 1.4 values for added mass. Therefore, we consider the ranges for both added mass and added damping to be mutually supportive. In either case, the range of applicability appears quite adequate for seismic response and normal steam-relief excitations of real power plant structures. However, applicability to blowdown accidents is probably questionable.

4. Multiple Members

4.1 Complexities Associated with Multiple Members

The fluid dynamic effects on multiple members are more complex than for a single isolated member. The arrangement of the members, space between members, motion of one member relative to another, and the generation of lift forces are all additional, important considerations. Added mass forces are no longer necessarily in line with the direction of motion, and lift forces may be generated which tend to act perpendicularly to the direction of motion [19, 20, and 21]. Damping tends to be higher than for single isolated members, and tight spaces between members, in particular, can increase the damping measurably [15, 22, and 23]. Multiple-member response, in general, is not too well understood. Current interest appears high as evidenced in recent publications, particularly relating to nuclear reactors. Many highly theoretical works are presented; some are rather complicated in terms of practical, everyday use in design analyses. Some experimental data are available to validate certain, often limited, aspects of the theoretical solutions. In general, additional experimental validation is needed, and the range of applicability of the various analytical techniques needs to be established.

Although many of the investigations are motivated by reactor internal concerns, the results published so far apply at best only to normal reactor operations and not to conditions associated with a blowdown accident. The flow rates and/or component motions are assumed small. Conditions associated with a blowdown accident are very likely beyond the range of applicability of the various techniques presented.

For our presentation, we separate our findings with respect to three types of structural arrangements:

(1) groups of cylinder, such as arrays,
(2) groups of cylinders, or a single cylinder, surrounded by a large circular cylinder, and
(3) coaxial flexible cylinders.

The first category can apply to the main steam-relief valve line next to the pressure suppression pool wall, an array of fuel elements in a fuel bundle, an array of fuel bundles in a spent-fuel storage rack, and an array of storage racks in a spent-fuel storage pool. The second and third categories can apply to the reactor-vessel internals.

4.2 Hydrodynamic Coupling for Groups of Cylinders

Closed form solutions using potential theory are presented in Refs. [19, 21, 24, 25, 26, 27, 28, 29, 30, 31, and 32] for added mass and lift forces for a group of cylinders. The solutions are given in terms of multiple summations and infinite series. The analyses are rather complicated but quite general; a group of different sized cylinders arranged arbitrarily can be handled, at least theoretically. A clear physical interpretation of the complex solutions is not immediately apparent. Some insight is provided in Refs. [2, 26, 28, and 29], where the solution is expressed in terms of "self-added" and "added" mass coefficients. The self-added mass coefficients characterize the hydrodynamic forces on a member from its own motion with all other members held stationary. The added mass coefficients characterize the hydrodynamic forces on a stationary member with other members in motion. Because potential theory is linear, reciprocity applies; i.e., the force induced onto member i from the motion of member j is the same as the force induced onto member j from the motion of member i.

Experimental comparisons with theory are given in Refs. [21,26, and 33] for a seven-member hexagonal array and a 3 x 3 square array. Comparisons between theory and experiment are made for a row of five cantilevered cylinders, a group of three cantilevered cylinders, and a group of four cantilevered cylinders [32] in terms of natural frequencies and mode shapes. The agreement between theory and experiment is good. Further comparisons were made in terms of acceleration response under steady-state sinusoidal excitation for the row of five cylinders and the group of three cylinders [32]. The agreement ranged from good to fair.

Although experimental confirmations are few, they are generally good for arrays of cylinders. Combining this with the excellent confirmation established for single isolated members that was discussed earlier in this report, we feel rather confident that the potential theory will adequately describe the added mass and lift forces for groups of cylinders. We would expect the range of applicability with respect to motion amplitude to be less than that for single isolated members because of the close proximity of the members. Whether or not the range of applicability of potential theory will be adquate under excitations of normally expected earthquakes is unknown. However, for the time being, we believe the potential theory can be assumed adequate based on the rather high range of displacement amplitudes applicable for single isolated members.

In Ref. [1], we addressed the nonuniformity of load among the cylinders of an array, the spacing between cylinders to result in zero coupling, and simplifying procedures to analyze multiple cylinders. Because of the lengthiness of the discussions, these are not included in this paper.

4.3 Hydrodynamic Coupling for Rigid Members Surrounded by a Rigid Circular Cylinder

A number of different member arrangements surrounded by a rigid circular cylinder have been investigated. Closed-form solutions based on potential theory are presented for coaxial cylinders (Refs. [14, 20, 28, and 33]), eccentric cylinders (Refs. [20] and [28]), and an array of cylinders surrounded by a cylinder (Refs. [20] and [28]). A finite element method was developed and applied to coaxial cylinders and to an array of cylinders surrounded by a circular cylinder [30, 34]. Analyses of coaxial cylinders using an incompressible viscous fluid theory are given in Refs. [15] and [35]. For the remainder of Section 4.3 of this paper, we will focus primarily on results pertaining to rigid coaxial cylinders. This is a simple model commonly used to simulate the internals of the reactor vessel under seismic excitation.

For two rigid coaxial cylinders in motion, with the annular space filled with fluid, the potential theory solution is expressible in a form quite convenient for design applications. The equations for the fluid forces on the inner and outer cylinders are given in Refs [13] and [33]. Some comparison with experiments for five cases of two coaxial rigid cylinders are given in Ref. [13]. The comparison was fair.

The finite element technique developed in Refs. [30] and [34] compared very well with potential theory in terms of added mass coefficients for two coaxial rigid cylinders. Therefore, the finite element technique is capable of duplicating the closed-form results. A comparison of the finite element technique with experimental results was presented in Ref. [30] for a 2 x 2 array of square cylinders surrounded by a circular cylinder. The agreement was reasonable.

A somewhat more sophisticated treatment of coaxial rigid cylinders is given in Refs. [15] and [35] using an incompressible viscous theory. The solution expressions are much more complex than those for potential theory. A comparison with experiment was made for a fixed outer cylinder and oscillating inner cylinder. The agreement between analysis and experiment was quite good, and it is noticeably better than the comparisons discussed earlier for the potential theory. A possible conclusion is that viscous effects may be important and perhaps should be included when analyzing coaxial rigid cylinders. More experimental comparisons are needed to confirm this possibility.

4.4 Hydrodynamic Coupling for Flexible Coaxial Cylinders

Coaxial cylinders with the inner cylinder analyzed as a flexible shell probably constitute a more realistic model of the internals of the reactor vessel than would coaxial rigid cylinders. Such a mathematical model was analyzed in Ref. [36] using an incompressible inviscid theory. The deformation of the inner cylinder is compared with experiment; the comparison was reasonable.

The case of three coaxial cylinders with the outer cylinder rigid and the inner cylinders flexible was analyzed in Ref. [37] using a compressible inviscid fluid theory.

A simpler case involving only one inner cylinder was compared with experiment in terms of natural frequencies. The agreement was very good.

A finite element analysis using the code NASTRAN was applied to two coaxial cylinders, the outer one rigid and the inner flexible [22]. A compressible inviscid fluid theory was used. A comparison between analytical natural frequencies and experimental data ranged from good to fair.

In general, based on the very limited amount of experimental comparison, the compressible inviscid fluid theory seems to do better than the incompressible inviscid potential theory. This indicates that fluid compressibility may be quite important to include when analyzing flexible members. Additional experimental confirmation is needed to fully establish this possibility.

4.5 Damping for Multiple Members

In Section 3.2 of this paper we explained that for fully submerged structures in a finite size container, radiation damping can generally be ignored. The contributions to added damping that remain are fluid viscosity and component impact. Both theoretical and experimental values for fluid viscosity damping have been published, although no analytical treatment of impact damping has been found. For experiments involving both fluid viscosity and component impact, no separation of the measured total damping into these two contributions was made. Establishing a fixed value of damping for a general multiple member structure is very difficult, if not impossible, because damping can be significantly influenced by member arrangement, spacing, and relative motions among the members.

Analyses were carried out for two coaxial cylinders using a viscous fluid theory [15, 35]. Three fluids were investigated in Ref. [15], and the theoretical damping was compared with the experimental; the agreement was quite good, indicating it is possible to obtain reliable damping values theoretically. Agreement was not as good in Ref. [35], where, by comparing the theoretical and experimental oscillatory motion amplitudes, it was determined that the theoretical damping underestimated the actual by a measureable amount.

Experimentally determined damping from water viscosity is presented also in Refs. [14] and [32]. It was shown in Ref. [1] that the test data for multiple members contained in these four references are mutually supportive.

Some measurements of total damping in actual reactors and models of reactors are reported in Ref. [38]. The values are 2 to 5% for core-barrel beam modes, 1 to 2% for core-barrel shell modes, 2 to 5% for guide tubes. These values are measured under low-displacement amplitudes on actual reactors. When the coolant is flowing, the damping increases with increasing flow rate, giving rise to core barrel damping ranging from 8.8 to 12%. In the opinion of the authors of Ref. [38], a significant contribution to the total damping resulted from component impact, particularly while the coolant was flowing. Component impact was, therefore, very possibly responsible for a major part of the 8.8 to 12% damping measured. Unfortunately, no separation between fluid viscosity effects and component impact was made. Consequently, the usefulness of the damping values is limited for general application because the component impact contribution could vary from one reactor design to another.

Further evidence that component impact contributes significantly to the damping was found in Ref. [31]. The effect of tube-support interaction on the dynamic response of heat-exchanger tubes was examined. The total damping measured was from 2 to 7.5%. Whereas it was felt the combined structural damping and fluid viscosity damping should have been approximately 2%. Again, no separation between component impact and other contributions was made.

5. Conclusions and Recommendations

5.1 Idealized Single Isolated, and Multiple, Members

Hydrodynamic effects on submerged single isolated members are fairly well understood. The added mass and added damping concept is adequate under seismic and normal steam-relief excitations; however, it is probably inappropriate for blowdown accidents. The potential theory will accurately give the added mass values, and tabulated results are available in the literature for a wide variety of single member geometries. Values for added damping are generally determined experimentally, and values are published for single isolated specimens of small sizes; i.e., up to 3.0 in. in diameter. To project these values to structural sizes of concern, we devised an extrapolation technique based on the published data and established information for the damping of water sloshing in pools. This gave the damping values for the structures of concern shown in Table 1.

For multiple rigid members under seismic and normal steam-relief excitations, the concept of added mass and added damping seems also to apply, and the added mass effect can be calculated using potential theory. Analytical description of the added mass effect involves "self-added" and "added" mass coefficients. The first characterizes the force on a member from its own motion with other members stationary, while the second characterizes the force on a stationary member from the motion of other members. Some published values for these coefficients are available for certain simple multiple member arrangements.

In the case of coaxial rigid cylinders, the potential theory solution can be expressed very conveniently for design applications. The inertial forces are given in terms of the mass of the fluid displaced by the inner cylinder and the mass of fluid filling the interior of the outer cylinder in the absence of the inner cylinder. In a more sophisticated analysis, an incompressible viscous fluid theory was used instead of the potential theory. The results generally agreed better with experiments than did the potential theory. This indicates that viscosity effects may be important for coaxial cylinders.

Coaxial flexible cylinders probably provide a more accurate model for the reactor internals than do coaxial rigid cylinders. Analytical treatments generally involve a compressible inviscid fluid theory and are fairly complex. Much needs to be explored for this case before conclusions can be drawn regarding design oriented methods. Interest in this area is currently high.

Damping for multiple members is presently a broad, imprecise topic, mainly because of its dependence on member arrangement, gap size between members, member geometry, and whether the member motions are in-phase or out-of-phase.

Table 1. Representative sizes and natural frequencies of structures of concern.

Structure	Excitations	Size	Natural frequency	Condition	Added damping % of critical
Fuel elements		~ 0.5 in. D			≤4.2
Fuel bundles, BWR		~ 5.5 x 5.5 in.	~3 Hz[a]	In water	≤0.55
fuel bundles, PWR		~10 x 10 in.	~3 Hz[a]	In water	≤0.33
Fuel racks: firm (1)[b]	Seismic		17 to 33 Hz	Full and in water	
Fuel racks: firm (2)			10 to 20 Hz	Full and in water	
Fuel racks: firm (3)			6 to 9 Hz	Full and in water	
Fuel racks: firm (4)			~ 12 Hz	Full in air	
Fuel racks: firm (4)			~ 10.5 Hz	Full in water	
Fuel racks: firm (5)			~ 1.15 Hz	Full in water	
Main steam-relief valve line[c]	Pressure relief	8 in. D, 72 in. L	0.5 Hz	In air	
	Blowdown-induced loads	8 in. D, 72 in. L	1.2 Hz	In air	
	Seismic	8 in. D, 396 in. L	0.02 Hz	In air	≤0.40 In water
		8 in. D, 396 in. L	0.04 Hz	In air	
		12 in. D, 72 in. L	0.8 Hz	In air	
		12 in. D, 72 in. L	1.8 Hz	In air	≤0.29 In water
		12 in. D, 396 in. L	0.03 Hz	In air	
		12 in. D, 396 in. L	0.06 Hz	In air	
Reactor core barrel	Blowdown-induced loads		40 Hz[a]	In air	
	Seismic		10 Hz[a]	In water	

[a] Approximate frequency values provided by NRC.
[b] The industrial firms generally wished to remain anonymous.
[c] Range of diameters and lengths provided by NRC.

Table 2. Applicable range of motion amplitude determined from added mass and added damping experimental data

Type of data	Specimen geometry	$A/D = U_m T/2\pi D$*
Added mass	Circular cylinder	0.8
	Sphere	1.4
	Circular cylinder	0.8
	Plate	0.8
Added damping	Circular cylinder diameter:	
	0.31 in.	0.32
	0.5 in.	0.4
	0.75 in.	0.43
	1.0 in.	0.5

*U_m = maximum oscillating velocity
T = period in seconds/cycle
D = specimen diameter or width
A = maximum oscillating displacement

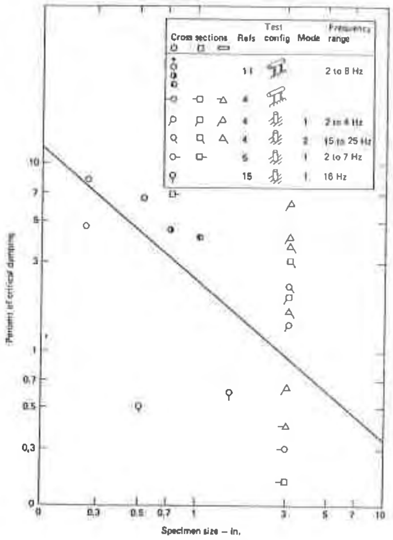

Fig. 1. A log vs log plot of the percent of added damping for various specimen cross sections and sizes.

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