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MOBILITY MEASUREMENTS OF A SIMULATED SEMI-INFINITE BEAM USING A LASER DOPPLER VELOCIMETER

L.E.Gilroy

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Approved by R.W. Graham:
Head/Hydronautics Section

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Abstract

An experiment involving the measurement of the vibratory response of a simulated semi-infinite beam was carried out at the Defence Research Establishment Atlantic (DREA) in support of the Ship Noise Project. The primary purpose of the experiment was to establish whether DREA's laser doppler velocimeter (LDV) would be an adequate tool for such measurements in a larger scale test. Secondary purposes included verification of the power flow finite element analysis method for a simple test case and examination of various damping treatments to determine the most effective. Results of the testing showed that the LDV was an excellent non-contacting sensor for the measurement of low level velocity signals providing that care is taken to check the focus of the laser to insure it maintains a 'lock' on the target and that the signal is kept at a reasonably small level. The use of DREA's milling table allowed for excellent position control and such a system would be ideal for a larger scale test. Of the various thicknesses of damping material applied, the 3/8" treatment seemed to be the most effective.

Résumé

Une expérience touchant la mesure de la tenue aux vibrations dans un faisceau semi-infini a été effectuée au Centre de recherches pour la défense Atlantique (CRDA) dans le cadre de l'étude sur les bruits de navires. L'expérience visait surtout à établir si le vélocimètre Doppler à laser (VDL) du CRDA pouvait s'avérer un outil efficace pour effectuer les mesures de tels essais d'envergure. L'expérience visait aussi à vérifier la méthode d'analyse par éléments finis de la puissance d'un écoulement (PFFEA) d'un simple test élémentaire et à étudier divers traitements d'amortissement pour déterminer lequel est le plus efficace. Les résultats des essais ont démontré que le VDL peut être un excellent capteur sans contact pour la mesure des signaux de faible vélocité si l'on prend soin de vérifier que le laser est focalisé et qu'il accroche bien la cible et si l'on garde le signal à un niveau relativement bas. L'utilisation de la table à fraiser du CRDA, idéale pour un essai de grand envergure, a permis de bien contrôler le positionnement. De tous les matériaux d'amortissement appliqués, celui de 3/8 po semble être le plus efficace.

DREA TM/97/201

Mobility Measurements of a Simulated Semi-Infinite Beam Using a Laser Doppler Velocimeter

by

L. E. Gilroy

Executive Summary

Introduction

For the last several years, Defence Research Establishment Atlantic (DREA) has sponsored the development of a novel numerical method for the analysis of high frequency structural acoustic and vibration response called the power flow finite element analysis (PFFEA) method. This method is based on a vibrational conductivity approach to high-frequency dynamics in which vibrational energy flow is modelled using an analogy based on heat conduction with convective losses. The development has been done in support of the Ship Noise Project whose objective is to provide DND with the expertise and tools necessary to deal with issues related to underwater noise from naval vessels. It is expected that this analysis tool, when completed, would be used to either optimize a structural arrangement to minimize high frequency radiated noise or to examine existing structures to isolate noise-producing elements.

At its current state of development, the PFFEA method is capable of predicting energy flow in many complex plate and beam structures, but does not yet include a capability for predicting the effects of dense fluid (water) loading or for predicting radiated noise. The existing software has been validated against theoretical solutions available in open literature and a limited set of simple experimental data, but has yet to be validated against a 'real-world' problem. To support the further validation of the PFFEA method, DREA has embarked on a series of experiments involving plate/beam structures of increasing complexity. This report discusses the first such experiment which involved examining a point-excited simulated semi-infinite simple beam. The main purpose of this trial was to establish measurement methods valid for the frequency ranges of interest which could be applied to a larger scale trial involving a single stiffened plate. Further validation of the current PFFEA method was a secondary goal of this trial as was the evaluation of various damping treatments to determine the most effective.

Principal Results

The specimen tested was a flat bar which was point-loaded at one end using an electromagnetic shaker. The other end was coated on both sides with an elastomeric damping material which was clamped into a vise. The arrangement was placed on a movable table and a laser doppler velocimeter (LDV) was used to measure the surface velocity of the vibrating beam as the table was moved past the laser beam. Recordings were made of the beam velocity with respect to the input force.

Results of the testing showed that the LDV was an excellent non-contacting sensor for the measurement of low level velocity signals. It was noted during the testing that care must be taken to check the focus of the laser to insure it maintains a 'lock' on the target to keep the signal at a reasonably small level. Velocities in excess of about 2mm/s caused problems with the system, although the system is nominally capable of measuring signals from 1m/s to 1μm/s. The use of the milling table allowed for excellent position control and such a system (if available) would be ideal for a larger scale test.

Of the various thicknesses of damping material applied, the 3/8" treatment seemed to be the most effective. Further assessment of the damping treatment will be made in a future report which compares the predicted and experimental results.

Future Plans

The next experiment planned will involve measuring flexural vibrations in a single-stiffened panel with dimensions on the order of 1m by 2m. It is hoped DREA's larger NC milling machine could be used in the same way the smaller mill was used for this trial. A further experiment could involve the use of the DREA Acoustic Calibration Barge as the structure to be tested to allow for a more realistic test bed.

Contents

1 Introduction

For the last several years, Defence Research Establishment Atlantic (DREA) has sponsored the development of a novel numerical method for the analysis of high frequency structural acoustic and vibration response called the power flow finite element analysis (PFFEA) method [1, 2, 3, 4, 5]. This method is based on a vibrational conductivity approach to high-frequency dynamics in which vibrational energy flow is modelled using an analogy based on heat conduction with convective losses. The development has been done in support of the Ship Noise Project whose objective is to provide DND with the expertise and tools necessary to deal with issues related to underwater noise from naval vessels. It is expected that this analysis tool, when completed, would be used to either optimize a structural arrangement to minimize high frequency radiated noise or to examine existing structures to isolate noise-producing elements.

At its current state of development, the PFFEA method is capable of predicting energy flow in many complex plate and beam structures, but does not yet include a capability for predicting the effects of dense fluid (water) loading or for predicting radiated noise. The existing software has been validated against theoretical solutions available in open literature and a limited set of simple experimental data, but has yet to be validated against a 'real-world' problem. To support the further validation of the PFFEA method, DREA has embarked on a series of experiments involving plate/beam structures of increasing complexity. This report discusses the first such experiment which involved examining a point-excited simulated semi-infinite simple beam. The main purpose of this trial was to establish measurement methods valid for the frequency ranges of interest which could be applied to a larger scale trial involving a single stiffened plate. Further validation of the current PFFEA method was a secondary goal of this trial, as was the evaluation of various damping treatments to determine the most effective.

The specimen tested was a flat bar which was point-loaded at one end using an electromagnetic shaker. The other end was coated on both sides with an elastomeric damping material which was clamped into a vise. The arrangement was placed on a milling table and a laser doppler velocimeter (LDV) was used to measure the surface velocity of the vibrating beam as the table was moved past the laser beam. Recordings were made of the beam velocity with respect to the input force.

This report discusses the experimental procedure and the results of the measurements as well as any difficulties that arose during the trials and the suitability of the measuring system for future trials. Comparisons of the measured data with predicted results from the PFFEA method will be presented in a future report.

2 Experimental Procedure

The experiment was conducted in the DREA machine shop using a small milling table as the base for the specimen. The specimen used was a flat bar constructed of Type 304 stainless steel with a length of 750mm, a width (w) of 26.3mm (average) and a thickness (t) of 1.45mm. 500mm lengths of an elastomeric damping material (EAR Isodamp C-1002 [6]) were glued to each side of the flat bar over the last 250mm of the bar (leaving 250mm of damping material after the end of the bar for clamping purposes). For more information on this damping material see [7]. The thickness of damping material (t_{damp}) used varied during the trials. The first tests involved using a 6.4mm (nominal 1/4") thickness on each side of the bar. Subsequently 3.2mm (nominal 1/8") thick layers were added to each side in each of the following two trials. A sketch of the specimen is shown in Figure 1.

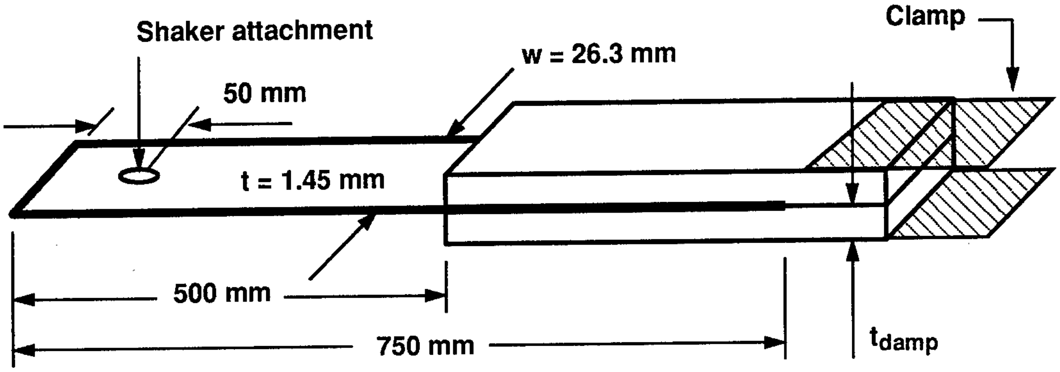

Figure 1: Sketch of Test Sample

A schematic of the test setup is shown in Figure 2. The specimen with the attached damping material is clamped in a vise attached to the milling table so that the steel beam is within several millimeters of the edge of the vise, but only the damping material is actually in the vise. The other end of the beam is attached to an electromagnetic shaker (B&K Type 4809 with a B&K Type 2706 Power Amplifier) which is used to apply a vibrating load to the beam. The attachment point is centred (width-wise) on the beam to induce only flexural waves in the beam.

The purpose of this method of attachment is to attempt to simulate an infinite beam. If the damping material were a perfect damper, energy travelling down the beam from the shaker will be absorbed by the damping material and there will be no reflection of energy. The vise is a potential source of reflections, so it is necessary not to have the steel actually within the vise.

A B&K Type 8200 force transducer was located at the connection point of the shaker to the beam and was used (in conjunction with a B&K Type 2635 charge amplifier) to measure the force applied by the shaker to the beam. The steel beam was attached to the force transducer using a thumbscrew and a tightening nut. A Melles Griot 55X Laser Doppler Velocimeter was located on a separate table arranged such that the laser beam targeted the steel beam at a right angle. The LDV's related units (Dantec Type 55 N 11 Frequency Shifter, Dantec Type 55 N 12 Frequency Shift Channel, and Dantec Type 55 N 21 Tracker Main Unit) were located on yet another nearby table. The output from the force transducer's charge amplifier and from the LDV unit were fed into an HP35670A signal analyzer. The engineering units on the analyzer were arranged so that the displayed signals were given in units of Newtons (for force) and metres per second (for velocity). Typically the analyzer's display was arranged to show the magnitude (in m/sN) and phase shift (in degrees) of the frequency response or mobility (velocity divided by input force).

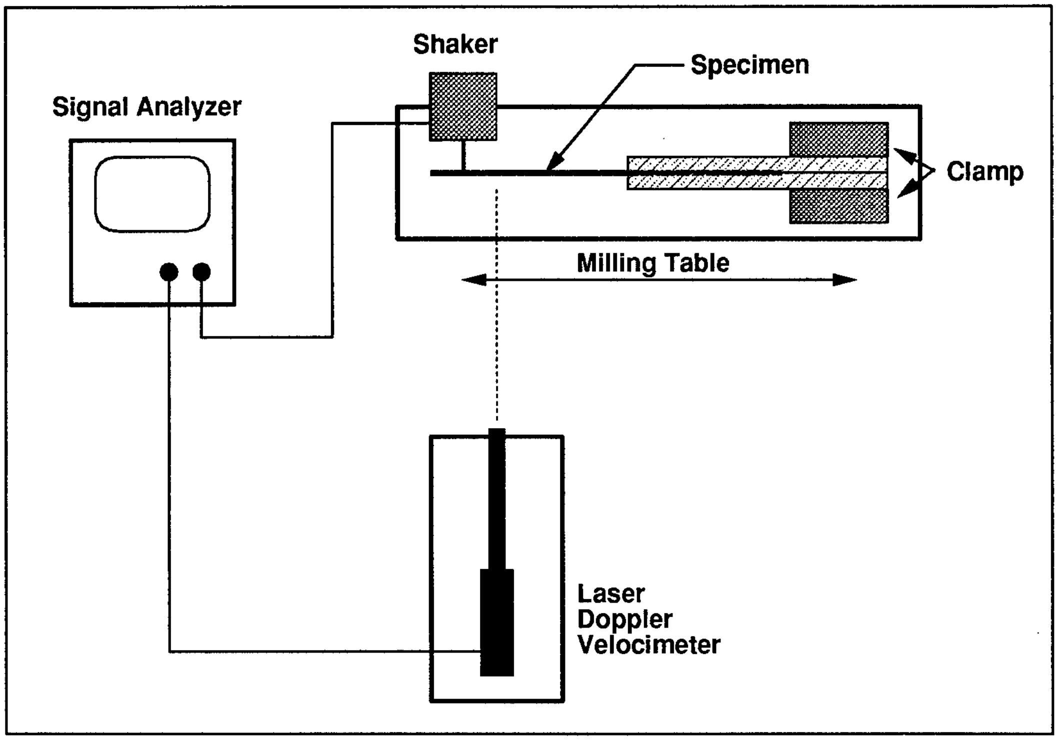

Figure 2: Schematic of Test Setup

For each set of tests, the first measurement taken was the input mobility where the mobility, as well as the component velocity and force, were measured at the drive point. Then mobility measurements were made at fixed length intervals as the milling machine was used to 'scan' the beam past the fixed laser beam. Five tests in total were performed using three different thicknesses of damping material (see test matrix in Table 1). There were two types of tests performed. The first type used a pure sine wave as an excitation to determine the exact distribution of power flow in the specimen. The frequency selected was 750 Hz which corresponded approximately to the peak of the loss factor curve for the damping material. The second type of test used band-limited random noise as input to the shaker. The purpose of broadband measurements were to determine the average or net power and energy distribution in the specimen which would correspond more directly with power flow conductivity model predictions. The input to the shaker covered a 400 Hz band centred around 750 Hz. In both cases, the

Thickness t_{damp}	Input signal	
	rms	pure sine
1/4"	x	x
3/8"	x	x
1/2"		x

Table 1: Test Matrix

signal analyzer was used as the source providing a signal to the shaker. Three configurations of samples were tested. The first specimen had a 6.4mm layer of damping material glued to each side of the steel bar. Layers of 3.2mm material were glued over the existing damping layers for the second set of tests and a subsequent layer was added for the final test. The first and second specimens were tested with both pure sine signals and band-limited random noise while the final specimen was tested with the sinusoidal input force only. Measurements were made from the force input point every 6mm over the bare steel to the leading edge of the damping material. In the last two pure sine tests, measurements were made past the edge of the damping material to the limit of travel of the milling table (the damping material itself proved an acceptable, though not ideal target for the LDV). With the zero point assumed to be at the force input, the leading edge of the damping material occurred at roughly 444mm and the limit of travel of the table was at the 600mm point. The milling table could be traversed with an accuracy of ±0.01mm.

Upon completion of this testing, further tests were conducted to determine some of the physical properties of the metal used, specifically, the damping ratio of the steel at the relevant frequencies and the actual Young's Modulus and mass density of the steel. To determine the damping ratios, a piece of the metal, without any damping material, was clamped in the vise and excited with broadband random noise using the shaker. The frequency response of the velocity (measured with the laser) with respect to the force was examined on the signal analyser. Four resonant peaks were noted around the 750 Hz mark. The beam was then excited in a narrow (25 Hz) band around each resonant peak and the marker functions of the analyzer were used to determine the actual resonant frequency and damping ratio. These tests were repeated four times and the results were averaged. The measurements were made at both the input point and 50mm from the input (to determine if there were any near-field effects of the attached shaker). A single trace was saved from each frequency and the traces were analyzed using the DREA program, DAMPFIT [7] which is used to predict resonant frequencies and damping ratios. A rectangular specimen of the material was also measured and weighed to determine the mass density. Finally, four tensile test specimens were constructed from extra material and tested using the DREA Tinnius Olsen tensile test machine to determine the Young's Modulus.

3 Experimental Results

3.1 Material Properties

Four tensile test specimens were prepared for testing on DREA's Tinnius Olsen tensile test machine. The slopes of the elastic portions of the resulting load-displacement curves were measured to determine the Young's Modulus of each section. The results are shown in Table 2. These are contrasted with a reference value of 193.1 GPa [8].

Test	Young's Modulus (GPa)
1	145.5
2	119.3
3	182.7
4	196.6
Ave.	161.0
±	35.2

Table 2: Measured Young's Modulus

The extreme variation in the measured moduli resulted from the nature of the material being tested. Stainless steel does not typically have the elongated straight line elastic slope characteristic of mild steels and some interpretation was necessary in determining the slope of the stress strain curve from the test machine used. A more modern test measurement and a larger number of tests would likely have resulted in a better determination of modulus. This does indicate that 304 stainless steel should be avoided when only limited testing can be performed to determine actual properties of test specimens.

The rectangular specimen was measured and weighed using a balance and the mass density was calculated to be 7910 kg/m^3. This compares favourably with the listed value for stainless steel of 8020 kg/m^3 [8].

The results of the measurements of the bare steel damping ratios are shown in Table 3. The first set of average damping ratios and standard deviations (σ) are for the measurements taken at the drive point while the second set are from those taken at the 50mm point. The results from the DAMPFIT code were taken from single samples from the 50mm drive point measurements. As can be seen from the table, the measurements are all consistent except for the DAMPFIT prediction at 890 Hz. There may be some error in the measurements for this resonant peak as it was a smaller peak on the side of the 894 Hz peak which could have influenced the measurements. Based on the measurement methods, the DAMPFIT prediction should be a more accurate value for this frequency.

Frequency (Hz)	Drive Point Avg. Damping Ratio (HP35670A)	σ (%)	50 mm Avg. Damping Ratio (HP35670A)	σ (%)	DAMPFIT Frequency (Hz)	DAMPFIT Damping Ratio
624.50	2.248E-3	1.20	2.194E-3	4.28	624.58	2.174E-3
749.50	1.855E-3	0.38	1.765E-3	3.23	749.75	1.858E-3
889.75	7.323E-4	1.65	7.283E-4	2.69	889.50	1.001E-3
894.25	9.516E-4	0.97	9.634E-4	1.35	894.23	1.035E-3

Table 3: Measured 304 Stainless Steel Damping Ratios

3.2 Sinusoidal Load Tests

The results of the tests will be divided in two sections based on the nature of the applied load. This section will deal with the tests involving the application of a pure sinusoidal load to the steel beam. There were three tests performed with this loading. The frequency of the applied load was 750 Hz and the specimen was tested with nominal 1/4", 3/8", and 1/2" thicknesses of damping material applied to each side. Measurements were made of the force and velocity at the input point and these results are shown in Table 4.

Thickness (in.)	Input Force (mN, rms)	Input Velocity (mm/s, rms)	Phase Difference
1/4	438.6	1.52	109.2°
3/8	433.4	3.65	113.2°
1/2	406.3	3.87	113.2°

Table 4: Measured Input Values for Sinusoidal Load Tests

The mobility measurements at other points are shown in Figures 3 through 7 with the first three figures being the individual tests while the remaining two figures are combinations of the test results. Note that, on the graphs, 0.0mm marks the drive point and 444mm marks the transition to the damping material.

It is immediately apparent from Figure 6 that the input mobility (the 0.0mm value) for the 1/4" test appears to be incorrect. This was noted on completion of this test and it was determined that the thumbscrew used to attach the beam to the force transducer was providing a poor target for the laser. The head of the screw was removed and the remaining top was machined to a smooth matte finish. This allowed subsequent measurements to be accurately determined. Interpolation of the Test 1 data indicates an input mobility of about 8.0 mm/sN (velocity of about 3.5 mm/s) would be a more appropriate value. Several velocity drop-outs

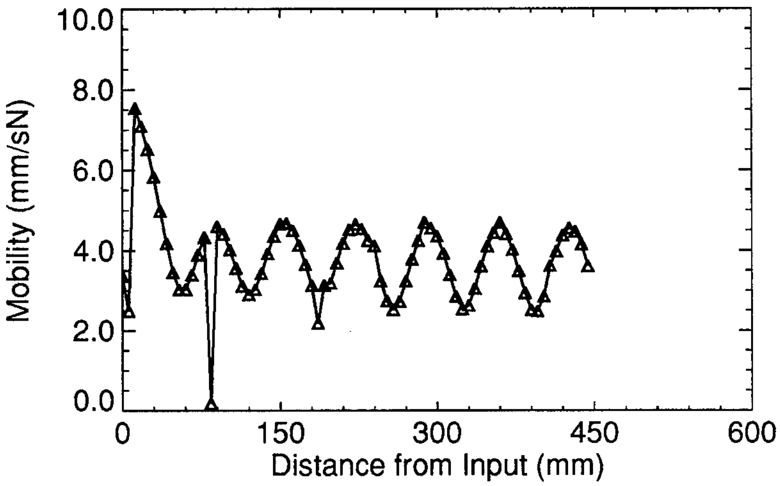

Figure 3: Beam with 1/4" Damping

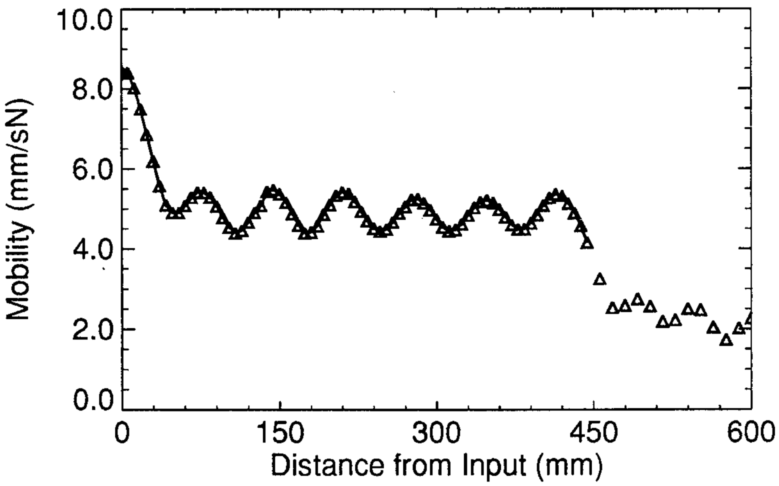

Figure 4: Beam with 3/8" Damping

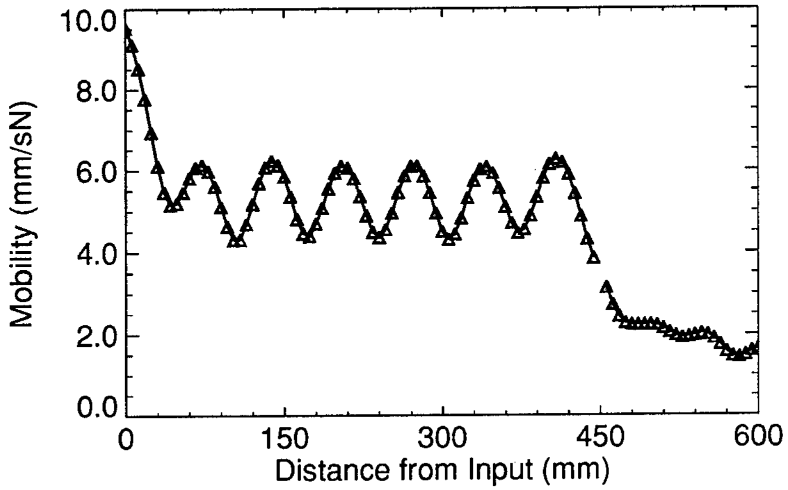

Figure 5: Beam with 1/2" Damping

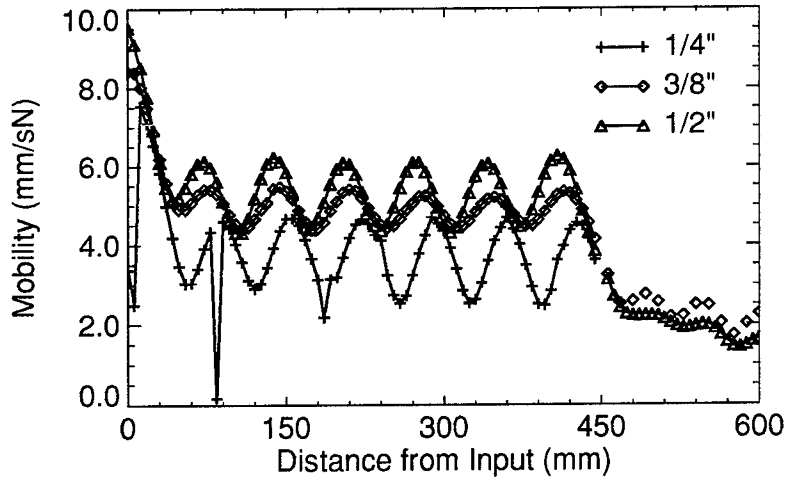

Figure 6: Combined Pure Sine Tests - Mobility

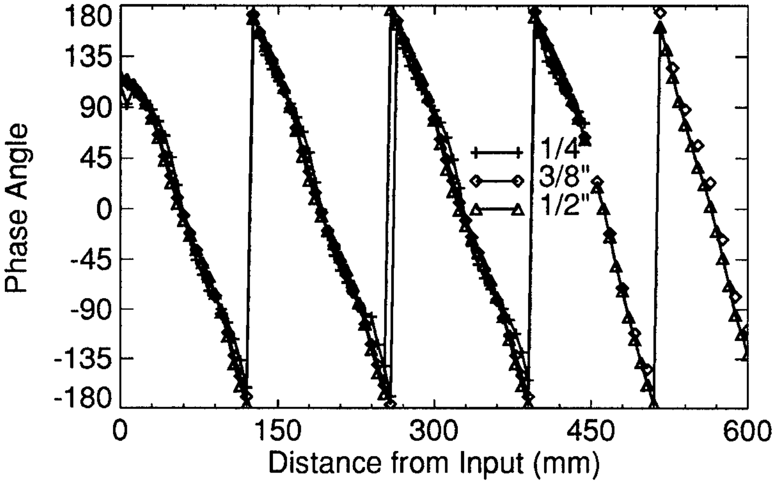

Figure 7: Combined Pure Sine Tests - Phase

were also observed in the first test. It was later determined that the laser lost focus at times and this was not checked during this test. This phenomenom was also observed in subsequent tests, but the laser was refocussed to determine an accurate reading at these points.

From Figure 6 it can be observed that the mean mobility rose as the damping layer becomes thicker. It was also apparent that the 3/8" damping treatment provided the greatest reduction in reflections which was deduced from the height of the oscillatory component of the curve. The increase in oscillation with the 1/2" treatment may result from the large structural discontinuity at the damping layer boundary. Such a discontinuity can cause energy to reflect back into the bare steel. An ideal treatment would likely involve a gradual change in damping thickness, however, this was not attempted during this experiment. The large oscillation at the start of each curve was a near-field effect from the point input. The ratio of the height of the oscillations after this near-field effect to the average value during the oscillations was about 0.20 for the 3/8" test, 0.35 for the 1/2" test, and 0.80 for the 1/4" test. It can also be observed that in the region covered by the damping material (after 450mm) the levels dropped faster for the 1/2" treatment than the 3/8" treatment (no measurements were made for the 1/4" treatment).

Figure 7 shows that changing the thickness of the damping layer had virtually no effect on phase differences and that, except for the near-field effect, the phase varies in a linear fashion with distance from the input point.

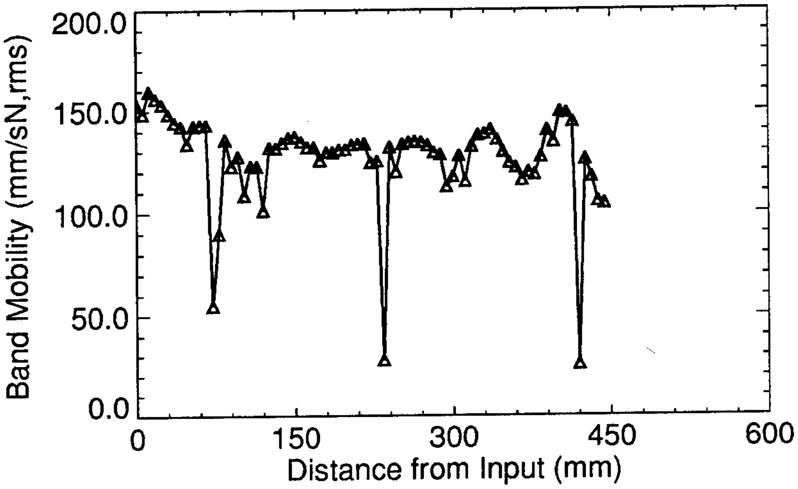

Figure 8: Beam with 1/4" Damping

3.3 Random Noise Load Tests

The second set of tests involved applying a band-limited random load through the shaker. The load was applied based on a 400 Hz band centred on 750 Hz. Two thicknesses of damping material were tested, 1/4" and 3/8". Measurements of band rms mobility were made and the results are shown in Figures 8 through 10 with Figure 10 being the two test results plotted together.

It can be seen by comparing Figures 8 and 9 that the quality of the measurement was much better in the second figure. The poor quality shown in Figure 8 was due to the loss of laser lock mentioned above which was not noticed with the 1/4" tests. As this effect was corrected for in the later tests, the data show an enormous improvement in quality, with the curve being extremely smooth and well-behaved.

By examining Figure 10, it can be seen that, while there is some decrease in the oscillatory nature of the 3/8" curve with respect to the 1/4" curve, there appears to be little difference in the mean mobility and in the input mobility which is in contrast to the pure sinusoid load curves. Also, in both cases, the oscillations increased towards the damped section of the beam. The reason for this is not readily apparent.

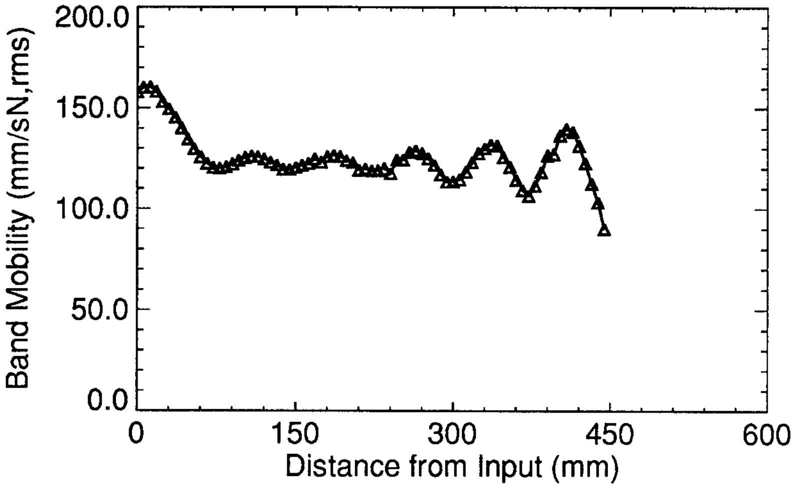

Figure 9: Beam with 3/8" Damping

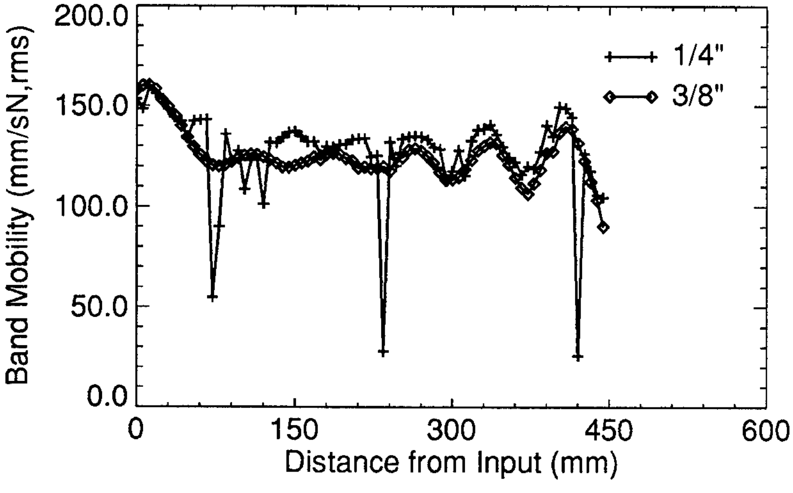

Figure 10: Combined RMS Tests - Mobility

4 Conclusions

An experiment involving the measurement of the vibratory response in a simulated semi-infinite beam was carried out at the Defence Research Establishment Atlantic in support of the Ship Noise Project. The primary purpose of the experiment was to establish whether DREA's laser doppler velocimeter would be an adequate tool for such measurements in a larger scale test. Secondary purposes included verification of the power flow finite element analysis (PFFEA) method for a simple test case (which will be discussed in a later report) and examination of various damping treatments to determine the most effective.

Results of the testing showed that the LDV was an excellent non-contacting sensor for the measurement of low level velocity signals. It was noted during the testing that care must be taken to check the focus of the laser to insure it maintains a 'lock' on the target and to keep the signal at a reasonably small level. Velocities in excess of about 2mm/s caused problems with the system, although the system is nominally capable of measuring signals from 1m/s to 1μm/s. The use of the milling table allowed for excellent position control and such a system (if available) would be ideal for a larger scale test.

Of the various thicknesses of damping material applied, the 9.5mm (3/8") treatment seemed to be the most effective. Further assessment of the damping treatment will be made in a future report which compares the predicted and experimental results. An ideal damping treatment would have shown no oscillatory behaviour in the beam.

The next experiment planned will involve measuring flexural vibrations in a single-stiffened panel with dimensions on the order of 1m by 2m. It is hoped DREA's larger NC milling machine could be used in the same way the smaller mill was used for this trial. Given the success of the measurements made in this trial, the LDV will be used as the velocity sensor in the upcoming experiment as well.

Acknowledgements

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An experiment involving the measurement of the vibratory response of a simulated semi-infinite beam was carried out at the Defence Research Establishment Atlantic (DREA) in support of the Ship Noise Project. The primary purpose of the experiment was to establish whether DREA's laser doppler velocimeter (LDV) would be an adequate tool for such measurements in a larger scale test. Secondary purposes included verification of the power flow finite element analysis method for a simple test case and examination of various damping treatments to determine the most effective. Results of the testing showed that the LDV was an excellent non-contacting sensor for the measurement of low level velocity signals providing that care is taken to check the focus of the laser to insure it maintains a "lock" on the target and that the signal is kept at a reasonably small level. The use of DREA's milling table allowed for excellent position control and such a system would be ideal for a larger scale test. Of the various thicknesses of damping material applied, the 3/8" treatment seemed to be the most effective.

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semi-infinite
vibration
power flow
high frequency
damping
experiment
viscoelastic

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