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High-Speed Rail IDEA Program

Vibration Measurement of Rail Stress

Final Report for High-Speed Rail IDEA Project 30

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TRANSPORTATION RESEARCH BOARD
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Vibration Measurement of Rail Stress

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ABSTRACT

Measurement of contained force in railroad rails is among the most significant issues in rail safety and track maintenance management, with implications for operation of high speed passenger trains on freight railroad trackage. Current techniques for that measurement are imprecise, time consuming, and expensive. This project develops a new technique, using rail vibrations and laser vibrometry, for the measurement of contained rail force.

The project has developed a finite element code ancillary to the technique, it has numerically simulated the measurement procedure to elucidate practical issues that may arise, and it has demonstrated the ability of the technique to infer load in laboratory and test-bay settings. Preliminary field tests have also been conducted.

We have shown that the proposed technique can be used to accurately measure contained load in rail. We have discovered, and illustrated, a number of aspects that must be (and now largely are) understood and accounted for before the concept can be used in the field. This report summarizes the results of the and concludes with recommendations for further development and a summary of the final panel discussions.

Keywords: rail stress, rail force, vibration, neutral temperature, nondestructive evaluation

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EXECUTIVE SUMMARY

Contained stress in rails, due principally to thermally induced expansion results in large longitudinal loads that can lead to broken rails and track buckling, or "sun kinks". Broken rails and track bucklings are leading causes of serious mainline derailments. The consequences for safety, reliability and rail efficiency are significant. The ramifications of both safety and service reliability are magnified where high-speed passenger trains operate on freight railroad lines. Furthermore, fluctuations in rail stress can contribute to fatigue and thus premature failure.

For all of these reasons, the need for a means of measuring contained stress has long been recognized. This is supported by TRB Committees A2M01 (Track Structure and Design), A2MO5 (Guided Intercity Passenger Transport), and A2MO6 (Railway Maintenance) who have all identified the problem as an important research need. Currently there are no practical methods for cost-effective field measurement of stress levels in rails. The objective of this project has been to develop a technology that will enable such measurements.

Here we have developed the principles needed for stress determination by measurements of rail vibration wavefunctions, as measured using laser vibrometry scans and lock-in amplifier techniques, the instrumentation for which has advanced substantially in recent years. Precise scans of vibration patterns were shown to reveal the state of stress of the rail. The work involved numerical simulations and laboratory proofs.

The technique requires the precise measurement of rail vibration profiles as a rail is vibrated at a prescribed frequency, after two or three fasteners are (temporarily) removed. The measured profile is compared with numerically calculated reference features, and the stress is inferred. Thus the project had two main thrusts. High-precision finite-element codes were developed for the prediction of reference vibration profiles. High precision laboratory techniques were developed to measure those profiles. Tests on rails loaded in compression to 100,000 pounds showed the expected dependence on stress. These test-bay measurements were found to have a precision equivalent to 2 degrees F (or 5000 pounds). The finite-element predictions for reference properties were less precise, corresponding to an error of about 13 degrees F. This latter error exceeds our target (10 degrees) by a small amount. Approaches for addressing this in the future are discussed.

Field work identified an additional issue that will arise in practice, that rails can experience small and intermittent changes in structure during a test. If uncontrolled, or uncompensated, such changes can adversely impact the interpretation of the measured vibration profiles.

Numerous procedures for addressing the remaining issues are discussed. We anticipate, after further development, having proofed a new prototype portable apparatus with potential for significant impact on rail operations. Stress management will become more efficient (in track time, personnel costs and track damage) with positive consequences for operation efficiency and safety.

BACKGROUND AND OBJECTIVES

The widespread adoption of continuous welded rail on railroad mainlines has improved ride quality and reduced both maintenance costs, and dynamic loads that can damage track structure. However, a problem that has long been recognized is the contained stress in rails that is due to thermally induced expansion and contraction, and the effects of locomotive traction and train braking. In continuous welded rail, bolted connections are unavailable to relieve that stress. This results in large longitudinal loads that can lead to a number of problems.

Tensile stresses due to decreased rail temperature can lead to broken rails, while compressive stress due to increased rail temperature can cause track buckling, or "sun kinks". The resultant effect on safety is of significant consequence to the railroad industry. Analysis of recent FRA accident/incident statistics show that various types of broken rails and track buckling are the leading causes of serious mainline derailments (as measured by average number of cars derailed per accident.) These causes alone accounted for over 20% of all the derailed cars over the five-year period 1994-1998. Although the majority of broken rails and track buckles are detected before they cause a derailment, they still have a serious impact on service reliability. The ramifications of both safety and service reliability problems are magnified where high-speed passenger trains operate on freight railroad lines. Furthermore, fluctuations in rail stress can contribute to fatigue and thus premature failure.

For all of these reasons, a means of measuring contained stress in rails is extremely important for freight railroads in general, and lines with high-speed rail operations in particular. This is supported by Transportation Research Board (TRB) Committees A2M01 (Track Structure and Design), A2MO5 (Guided Intercity Passenger Transport), and A2MO6 (Railway Maintenance) who have all identified the problem as an important research need. For discussion, see the web sites at http://www.nas.edu/trb/about/a2m01ps.html, /a2m05ps.html, and /a2m06ps.html. Interest is not confined to North America; at the 1997 World Congress of Railway Research this problem was identified as high priority. Members of the railroad engineering and research community have told us that a portable practical means of measuring this type of stress would be ideal because it would enable track engineering personnel to spot-check locations where trouble is suspected. Currently there are no practical methods for this sort of field measurement of stress levels in rails. The objective of this proposal is to develop technology that will enable such measurements.

Rails are laid at a temperature (the initial "neutral temperature") calculated to minimize the total risks associated with rail breaks and buckling. If the neutral temperature is known, the stress is inferable from the current temperature and the thermal expansion coefficient of the rail. Conditions of high stress would then be predictable. Unfortunately neutral temperature can change after track is laid, due to longitudinal creep associated with locomotive traction and braking. The essential problem is therefore often described as determination of a rail's neutral temperature, related to stress and temperature by simple math. Stress is, however, the more natural quantity, and endeavors to assess neutral temperature are usually recast as simultaneous measurements of temperature (simple) and stress (difficult.)

Rail stress can be measured by rail uplift or by application of strain sensors. Both have significant limitations. Measurement of stress by rail uplift is cumbersome and not very precise[1]. It requires removal of the fastening devices from a large number of ties and requires significant track time and effort. Use of strain gages limits measurement of strains to specific locations where the gages have been installed and where cutting/destressing have been implemented to provide a reference state to enable subsequent absolute force determination. Installed strain gages can degrade or detach.

The measurement of stress in rail is sometimes referred to as the "holy grail" of railroad track engineering and maintenance. Quick and reliable methods for measuring stress in rail would improve both the safety and efficiency of railway operations. This is a long-standing problem, and with increasing axle loads and train speeds this problem is becoming even more critical. New methods for measuring stresses in metal members could also be valuable for evaluating stresses in other items of interest to the railroad industry, for example wheels and bridges and indeed throughout the national transportation infrastructure.

A variety of techniques have been proposed in recent decades for nondestructive and efficient field measurements of absolute contained rail stress. Currently there are two techniques being used or tested, neither of which is totally satisfactory. These are the rail uplift technique (see e.g. Kish et al[1]) and Salient System's remote sensing module. Another concept that has been considered is to take advantage of the known sensitivity of bending vibrations to contained longitudinal stress. Related investigations using rail vibrations with a view towards determining stress in rails, have been by Beliveau and others, with no success.

Here we have approached the problem from a significantly different perspective. We have developed the principles needed for stress determination by measurements of rail vibration wavefunctions, as measured using laser vibrometry scans and lock-in amplifier techniques, the instrumentation for which has advanced substantially in recent years. Precise scans of vibration patterns have been shown to reveal the state of stress of the rail. The work involved numerical simulations and laboratory proofs.

IDEA PRODUCT

We anticipate, after further development, having an apparatus consisting of a laser vibrometer, a (~2 meter) scan platform upon which it rides, an (~20 lb) electromagnetic shaker, small accelerometers and related electronics, all controlled by an integrated PC. The apparatus will be portable on a high-rail vehicle or small truck, positioned either manually or automatically, and be capable of being operated by rail personnel. Total cost of the apparatus will be of the order of $50,000. Tests will require removing a small number (2 or 3) fasteners, and require of several minutes per test.

Our conversations with rail engineers show potential for significant impact on rail operations. Stress management will become more efficient (in track time, personnel costs and track damage) with consequences for operation efficiency and safety.

CONCEPT AND INNOVATION

The basic physics of the proposed approach is similar to that exploited in the rail uplift method [1]. There a vertical force is applied to the mid section of a (~30m) span of rail (released from fasteners) sufficient to raise the rail a specified amount. Contained compressive force reduces the effective rigidity of the rail and decreases the force needed to cause the specified displacement. The method is cumbersome, requiring large forces and equipment mounted on a full size rail car. It is also time consuming and, because of the need to remove many fasteners, considered somewhat destructive. The high precision needed for the measurement of vertical displacement is an additional difficulty. That the method cannot be applied when rail is in compression is a further problem.

The decreased rigidity associated with contained compressive load (or increased rigidity associated with contained tension) also manifests itself as decreased (increased) dynamic rigidity and corresponding vibration frequency. Beliveau and co-workers [2] proposed using the effect to assess rail stress, but found that variability in rail supports was too great; the effect of interest was masked by the support variability.

The decreased rigidity associated with contained compressive load (or increased rigidity associated with contained tension) also manifests as a change in the wavenumber (inverse of wavelength) of vibrations at specified imposed frequency. Thus detailed measurement of rail vibration profiles at fixed frequency, as a function of position along the rail between supports, ie., how the vibration profile varies in space, will allow inference of the contained load. Scanned laser vibrometry can do this. Most importantly, this dependence of wavenumber on load is independent of end conditions. It can be used to measure the stress. The need is for accurate measurements of wavenumber, and accurate understanding of the reference wavenumber (the value it would have in the absence of stress), and a comparison between them.

INVESTIGATION

The investigation had several phases. Initial work was numerical and analytical. This was followed by development of a first prototype apparatus in the laboratory, and then by its application to a test bay on rails under load. Finally, preliminary field tests were conducted.

A. DEVELOPMENT OF A FINITE ELEMENT CODE

A finite element code was developed for the prediction of the frequency-wavenumber relation for guided modes of an elastic waveguide of arbitrary cross section. The code was proofed against the known modes of a circular waveguide. Convergence of the results, as the mesh is refined, was established. This work is in press with the J Acoust Soc Am [3]. The results of the code are used to predict the reference wavenumber that will be compared with measured wavenumbers.

B. CALCULATIONS OF ERROR PROPAGATION,

The degree of apparatus and measurement precision necessary to infer neutral Temperature with the desired accuracy was estimated. Indications were that the clamp approach is more demanding (than is the guided wave approach) of precise knowledge of rail elasticity and dimensions. It was shown that our arbitrary target precision of 10 degree F in neutral temperature should be achievable with 1/2% accuracy in rail shape and rail moduli and 1/4% accuracy in measured lateral wavenumber - if we were to use a one meter scan. The requirements are less stringent (by a factor of 4) if a longer scan (by a factor of 2) is used. These precisions in rail properties are, we are told, reasonable.

C. NUMERICAL STUDY OF CLAMPS

It was suggested, as an alternative to scanned laser vibrometry, to isolate short sections of a rail and evaluate the free vibration frequency of that section to assess load. It was shown here that clamps of rigidity sufficient to provide the necessary isolation would be prohibitively large. It was recommended that the clamp approach be abandoned and resources concentrated on the scanned laser vibrometry approach. This recommendation was accepted by the review panel and the TRB.

D. FORMATION OF THE ADVISORY PANEL.

The advisory panel consisted of Martin Schroeder of TTCI, Hayden Newell of Norfolk Southern, Keith Hjelmsted (Associate Head of Civil and Environmental Engineering at UIUC and researcher in structural dynamics). It met on Oct 25, 2001.

E. INITIAL STAGES OF LABORATORY SET-UP.

Two 8' sections of new #136 rail were obtained. A laser vibrometer was purchased, and a track on which it can be (manually) scanned was constructed. A LabView code was written to take data and construct the desired digital lock-in. The rail was excited with the use of a small (5#) electromagnetic shaker. Preliminary measurements were made of the resulting displacement profile. These showed the expected dominant lateral bending waves, with the correct wavelengths. They also show that this small shaker, in spite of is size, produces a rail vibration that is readily discernable above noise.

F. THE RAIL MODULUS

The rail's modulus was successfully measured using longitudinal vibrations, with a precision that exceeded the estimated requirements.

G. FINITE ELEMENT CODE IMPROVEMENT

The code was further improved, and applied to 136# rail.

H. SIMULATED EXPERIMENTS

Simulated experiments were conducted. Numerical solutions of the elastodynamic equations governing rail vibration were analyzed by a prototype fitting procedure to extract best fit value of lateral bending wavenumber. To do this, the Finite Element Code had to be extended to the prediction of mode shapes as well as wavenumbers k, and wavenumbers and mode shapes were used to predict responses. "Measurements" of those responses were subjected to various possible random and systematic sources of error. The recovery of wavenumber was good. It was found that a 1% or more noise will be acceptable. The simulations also indicated the expected advantages of longer test sections. They also indicated that laboratory and field procedures would have to make two or more scans, at different positions on the web or head, in order to confidently account for both torsional and bending waves. Later, we used this program to simulate the effects of systematic errors in laser spot positioning; and found a good tolerance for such errors. These numerical simulations showed that our target precisions are indeed achievable, even with realistic levels of noise. This has been written and is currently in press with the J Acoust Soc Am[4].

I. LABORATORY WORK

Extensive work designing and proofing hardware was carried out.

Chief amongst the originally unanticipated challenges was our discovery of a small slow variations, or "drift," in the response of our laboratory rail to a nominally steady dynamic loading. Uncontrolled variations of its (several percent) magnitude would be unacceptable. This was a serious challenge for a while.

The "drift" was addressed by monitoring the rail vibration amplitude with a fixed accelerometer, and allowing the shaker's force output, and the rail response strength, to vary arbitrarily - often by tens of percents. This provided a continuous collection of data on the response of the rail that could be used to normalize the signal from the a laser vibrometer. The variations, it was discovered, were due to temperature fluctuations by a few degrees. Normally that would be unimportant, but it was exacerbated by a strong rail response sensitivity to temperature engendered by our operation at a resonance. Rather than attempt to fix the response amplitude at a constant, we elected instead to normalize on the fly to the signal from a fixed accelerometer attached to the rail, an accelerometer that essentially monitors the rail response. This reduced the drift to an amount of order 0.1% / 30 minutes - an amount that we showed later (using numerical simulations) to be tolerable. This remaining 'drift' is probably due to the accelerometer's own sensitivity to random temperature fluctuations - by one or two degrees F. The remaining very weak drift we learned to eliminate by performing a periodic re-calibration of the accelerometer against the laser vibrometer. It was anticipated (correctly it turned out) that temperature dependent "drifts" will be less important in field applications where structures are less resonant, and thus less sensitive to small changes in temperature. Furthermore, the ultimate use of a new, more rapid, scanner that can finish its data taking in less time, will further mitigate against this concern.

Scanning hardware was designed and installed, and laboratory scans at zero load were conducted. The system was designed to conduct scans at 1) two positions on the side of the rail, and on 2) one position on the top of the rail. These are needed to (1) control for the potential amount of torsional wave present in the rail and (2) to control for the vertical bending waves. Scans were found to be reproducible in the lab to within better than 0.1%, even if conducted on different days.

J. FITS OF THE LAB DATA

Fits to a sum of guided modes were undertaken.

We discovered a small random (average zero) error in the position of the laser spot on the rail. This was not expected, but it does not appear to be a critical issue as its only effect is to enhance effective noise levels. It was eventually ascribed to slips in laser alignment; the scan platform we built was not perfectly rigid.

We discovered a small and systematic difference in axial position (i.e. along the rail length) of the laser beam between the scans done at the two levels on the side of the rail. This lead to a systematic error in inferred neutral temperature. This problem was solved by including an extra adjustable parameter in the fit process, one that corresponds to the unknown constant error in positioning. The clear lesson was that the next hardware design needs to assure this vertical/axial positioning precision.

Scans were (and still are) done tediously and slowly by hand; it was decided that ultimate applications will require computer control and automatic scanning.

We measured the vertical bending waves, and found them to be negligible..

K. DESIGN OF TEST-BAY APPARATUS

We conducted extensive work on designing and proofing, and re-designing, procedures and hardware for measurements in the test bay. Data collection was designed to be conducted over a range of compressive loads up to a maximum of 100 kips.

The rail support was designed in a way that would leave the rail level and straight as loads were applied, so as to eliminate any need to re-align the laser scan at each load level.

We found that vibration amplitudes in the test bay remained high, comparable to those achieved in the lab. Signal to noise levels remain good.

Preliminary scans were taken in the test-bay. They showed all the features we wanted. They had good signal to noise, and they had the right dominant wavelength. Figure 1a below shows a typical result from a scan at a fixed position on the web, versus distance along the rail.

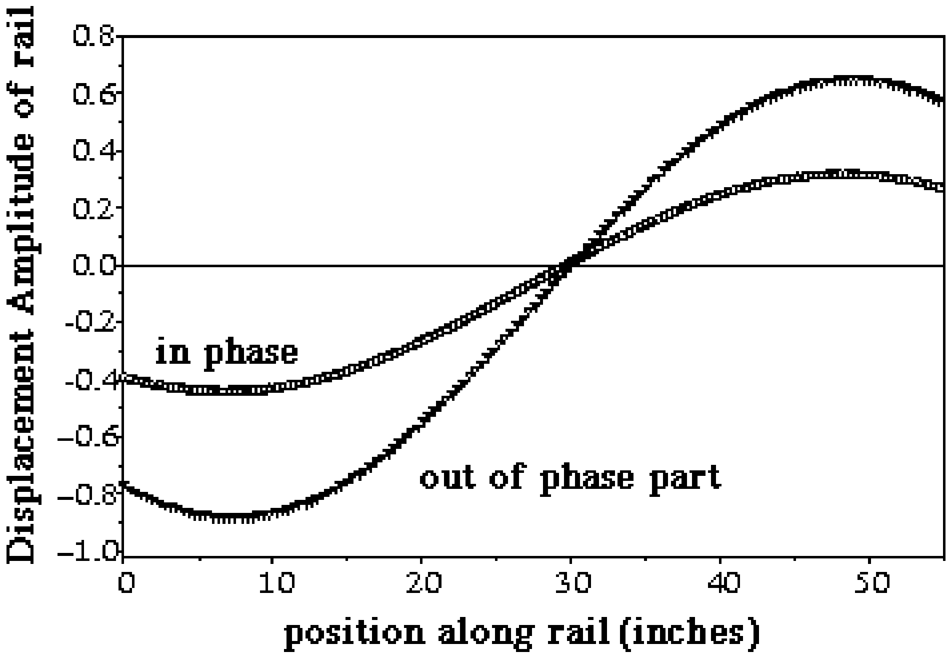

FIGURE 1a] Typical test-bay data showing rail displacement amplitude as measured by the laser, and normalized by the accelerometer. A wavelength of about 40 inches is apparent. The two "parts" of the dynamic amplitude represent the parts that are sinusoidal, and cosinusoidal, in time.

L. TEST-BAY DATA

Vibration data were taken over a range of compressive loads to a maximum of 100 kips. Highlights of the observations include:

Resonant frequencies varied with applied load, but not in the manner predicted by simple models proposed by others. As had been expected, and also seen by Beliveau, end-conditions vary more with applied load than does effective rail rigidity; resonant frequency cannot be used to infer load.

Drift remained slight and slow, as observed in the lab; it could be corrected for by the periodic re-calibration procedures developed to do so.

The contribution of vertical bending waves was measured to be slight; they could be ignored in the fit process.

The rail, even when attached to the loading apparatus and the end support, remained highly resonant; signal quality remained excellent.

Data-taking remained highly tedious. The prototype design allowed operator error to occur. Except for an unknown source of error at 50 kips (for which we have no reliable results), such errors were found to be compensateable with the right kind of later data analysis.

Errors included:

- a short span of positioning error related to the manual alignment;
  this was corrected by dropping this span of data from analysis.
- a constant offset in laser positioning between the scans at the two heights.
  corrected in post-processing.
- random errors, by a fraction of a mm, in the laser positioning
  equivalent to extra noise, and so with little impact.
- missing, or duplicated, points in the scan, related to operator error,
  corrected in post-processing

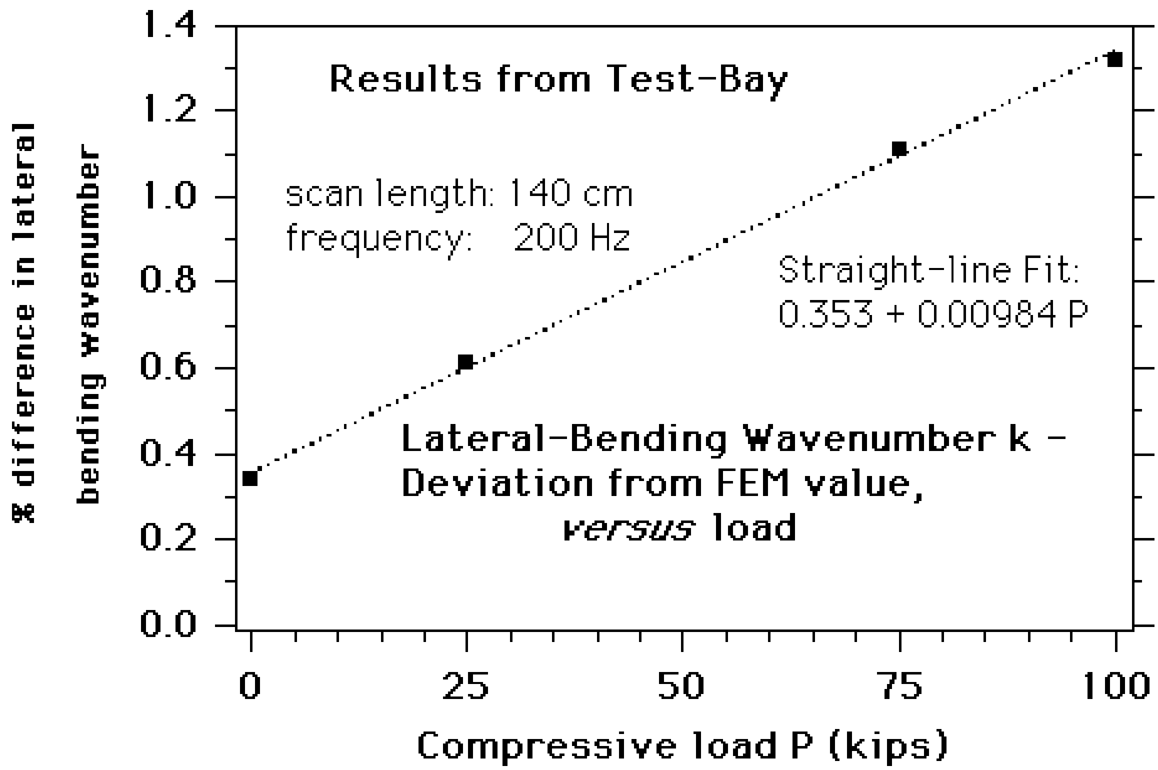

FIGURE 1b] The correspondence between load and recovered wavenumber is good.

M. ANALYSIS OF THE TEST-BAY DATA

The short spans of positioning error were removed from the data set, an extra fit parameter was introduced to compensate for the constant offset, missing or duplicated points were removed. The result of this analysis is given in the figure above. (Fig1b)

The quantity plotted vertically is the deviation of the lateral bending wave wavenumber in percent. The deviation is the difference between the measured lateral bending wave wavenumber, $k_{lateralbending}$, and the prediction of our theory for the zero-load case (this theoretical prediction is based on taking the AREMA standard for the rail shape, and modulus, and calculating the lateral bending wave from our FEM code.)

We note three main things in this plot:

The best-statistical linear fit (dotted line in figure) has the predicted slope, of 1.0% per 100 kips.

The measured data conforms closely to the straight line - this means that the measurement technique has good precision. Deviations are less than 0.05% - or about 2 degrees F. This is especially encouraging as we originally targeted 10 degrees F. So this part of the method works very well. This is slightly surprising, as the "slop" in the current apparatus is quite noticeable in the raw data, and in the imperfect rigidity of the laser scan platform. Corrections needed to be applied in the software fitting process to account for errors. This means that when we improve our apparatus (and we know how to do this) we will be able to greatly improve the precision - and/or manage to do as well using a shorter scan section. Even with the present apparatus, and notwithstanding the next paragraph, we can now reliably infer stress in our own piece of new #136 rail.

The intercept of 0.34% corresponds to a discrepancy between prediction and measurement even at zero load. This may be due to a difference between the AREMA standard for the rail shape and the actual shape. This may be fixable by doing some profilometry. If left unfixed, this translates to an error in recovered rail stress of about 13 degrees F, greater than our target, but not by much.

Potential methods for fixing this are:

- Rail profilometry
- Using a scan length that is longer (say by a factor of 2) to give a resulting drop (by a factor of 4) in the bad effect of that intercept. This is the easiest fix, and could be implemented virtually immediately. In short, we can say that the

method works, with a precision that is 13 degrees F *(56 inches/ scanlength)^2. By choosing scan length, one can obtain any desired precision.

• Do scans at two frequencies, and recover both effective rail profile and contained load. We tried this in the test bay, and found that the 56 inch scan we did corresponded to a too small a part of the wavelength at the chosen frequency of about 60 Hz. Wavenumbers at 60 Hz were recovered with poor precision. This would work better with a better laser platform and/or a longer scan range.

One may also note the absence of a data point at 50 kips. For some reason the slop in our laser platform was too intrusive here; it could not be corrected in software. The fits were bad, and the recovered lateral bending wavenumber was obviously wrong. So it is not included. One expects events like this to be eliminated by the proposed improved hardware.

The development of the apparatus, the test procedures, and their application in the test-bay, are discussed further in a paper currently in press with the J Sound and Vibration [5].

FIGURE 2] The PI, adjusting the laser vibrometer during preliminary field tests 8/23/03.

N. FIELD TESTS

Field tests were conducted on August 21, 23 and 28, 2003. Canadian National - Illinois Central made a new, un-installed, track-panel of 136# rail available to us (see photos) and gave us access to 110V power to run our equipment. A number of issues arose there that confirmed the wisdom of doing field tests at this stage of the project. These include:

High rail temperatures (it was a hot sunny day) caused the wax to melt and the accelerometer to fall off. The wax was replaced with a magnetic attachment.

The sun made it hard to read the lap-top screen; a hood was designed to shield it.

The in situ rail was much less resonant than the rail in the test-bay or the rail in the lab. There are, apparently, losses into the ties and ground, and only modest reflection of ~200 Hz vibrations by the fasteners. (indeed, we estimated an effective reflection coefficient of about 33%) Accordingly, almost any frequency could be used with equal ease. Although the signals were weaker than in the lab and test bay, they were still quite adequate. Tests were then conducted at 200Hz.

FIGURE 3. John Tuckett of CN-IC, and the PI, at the field test site 7/03

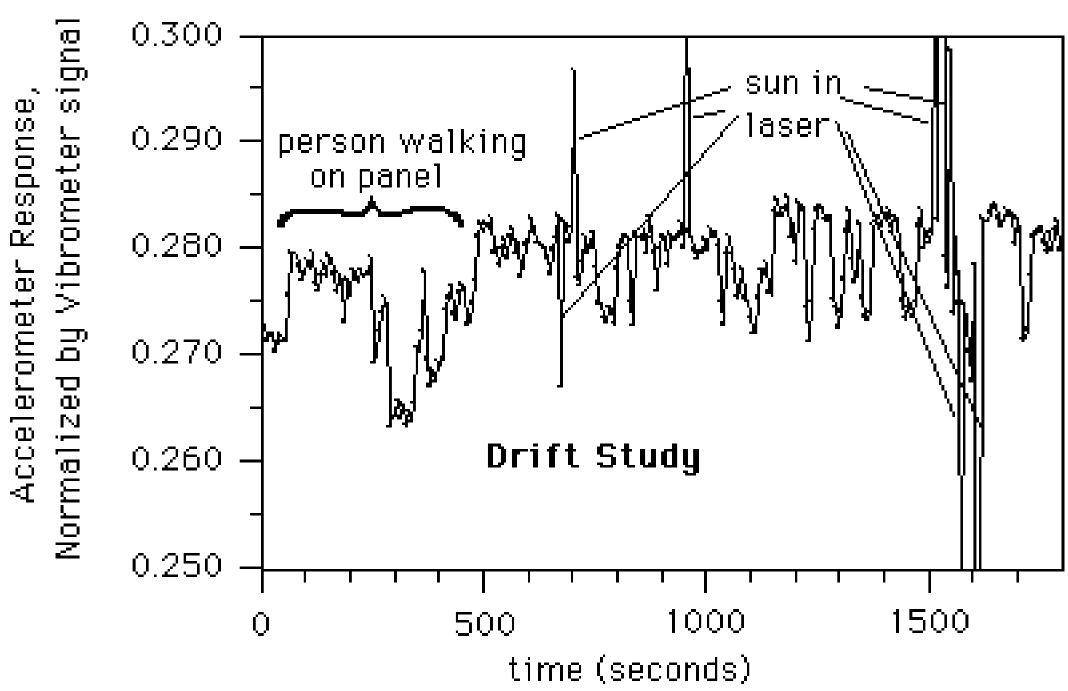

FIGURE 4.] A plot of the field work's drift study. The structure response varies over a period of 30 minutes.

Drift studies were repeated, to assess the natural fluctuations in rail response to a fixed dynamic load in the field. Recall that drifts in the lab and test bay were due to temperature fluctuations of a degree or so over a period of minutes, and were compensated for by periodic re-calibration of the accelerometer. The field-drift study showed a number of interesting features. The plot below is taken from 300 successive two-second data samples taken at a fixed point, separated by four seconds each. Ideally, all data points should be identical. Variations are due to random noise, and to drifts in structural response, and to a much lesser extent drifts in accelerometer sensitivity.

There are a number of observations to make in regard to this drift study..

• There are occasional glitches where the accelerometer response, as normalized by the laser signal, varies suddenly and by a large amount, and then returns to its original value. These correspond to times the sun got into the laser detector. They are not a critical issue, as such points can be removed from later analysis; they are obvious in the scan data. They will be less common when the laser can be mounted closer to the rail, or pointed away from the sun, or on a cloudy day, or when a well-designed hood is placed on the laser.

• the extended smaller glitches at 0-80 seconds and again at 230-500 seconds were purposefully induced, by having a person walk on the rail or the nearby ties while the data is being taken. Clearly the response of the rail varies as this happens. It is a lesson for further work, the rail structure needs to be kept undisturbed while data is being taken.

• There are intermittent shifts, between what appears to be two states differing by a few %. This behavior was not present in the lab or test-bay. It is too irregular to be compensated for in the manner prescribed for our test-bay work, and is the chief source of error in the field-work's load inference discussed below. The field work has identified this an important issue for further work, and we have a well-considered plan to solve it.

• Raw scan data taken on 8/28 is given in Figure 5, where obvious glitches are apparent, and therefore removable. Also interesting is the shift at about 11 cm. This corresponds to the time at which a freight train passed the field site, inducing substantial ground vibration. The track being tested has apparently shifted its response; the structure has changed. This was compensated by removing the first several points from the analysis. The scan data, after such fixing, is shown in Figure 6.

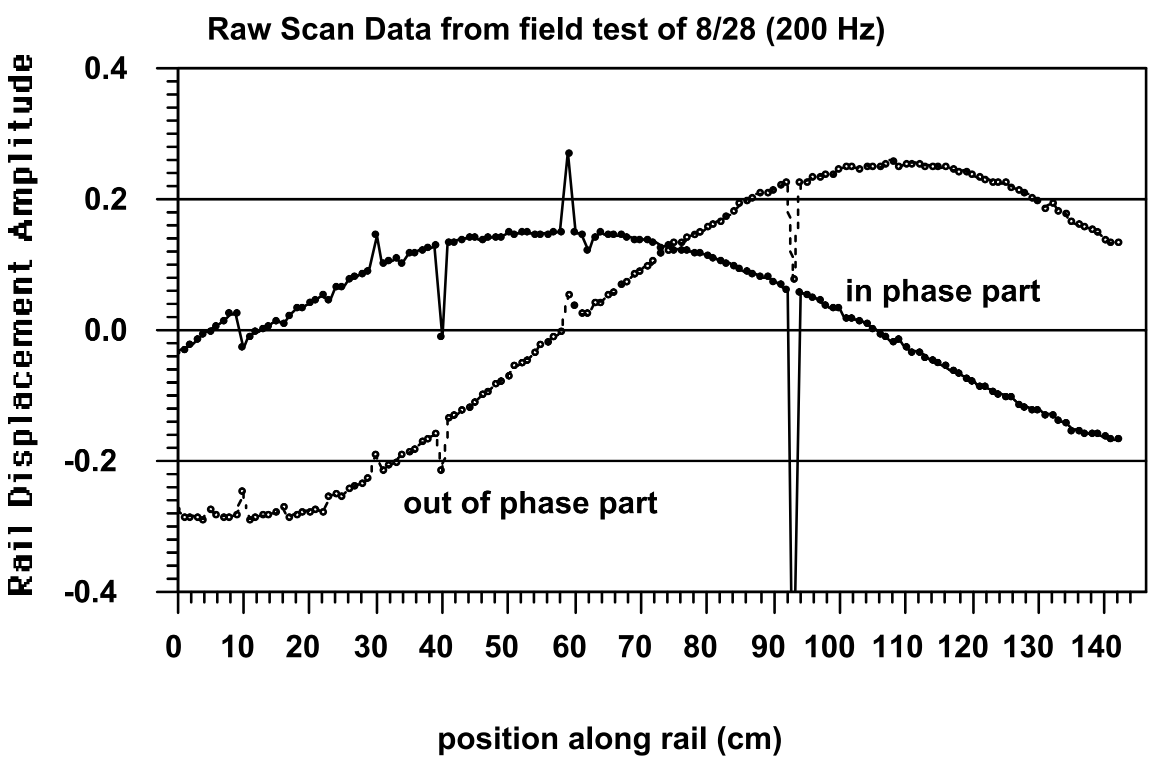

FIGURE 5] Raw data from field-work scan at 200 Hz.

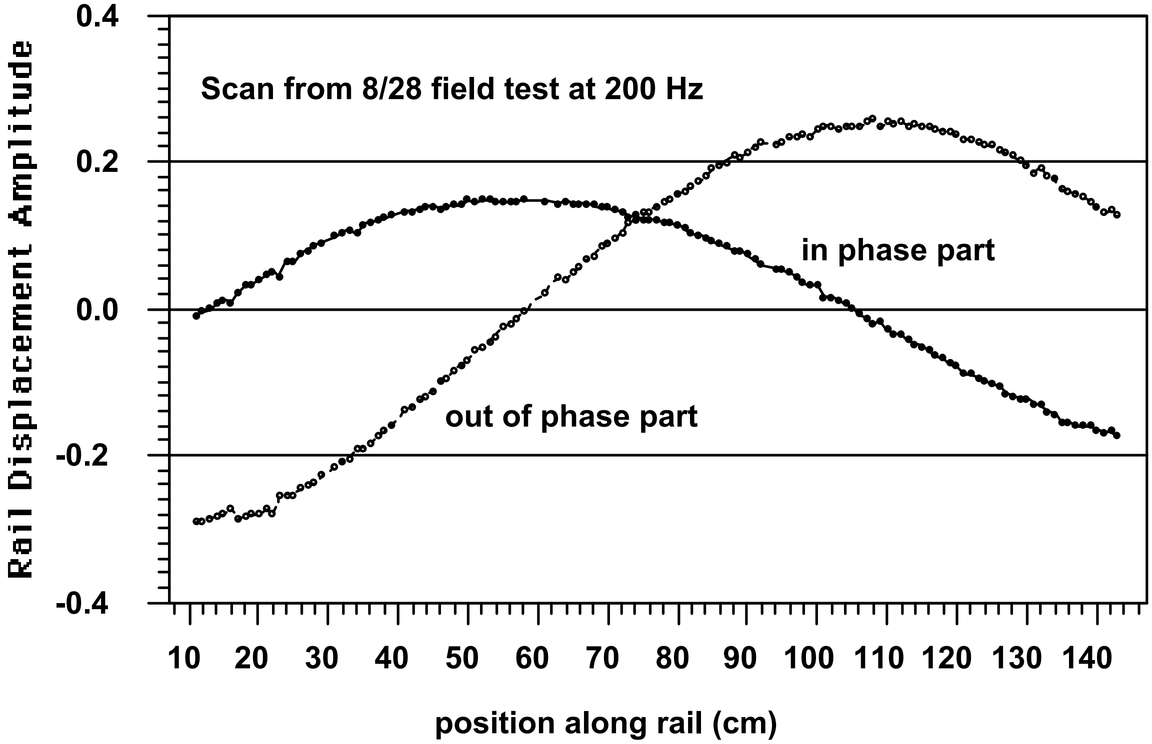

FIGURE 6] Corrected data from field-work scan

A wavelength of about 2 meters is apparent. Similarly, one can identify the wave as mostly a travelling wave (unlike that of the test bay where the wave was standing). Glitches still remain, but absent a rigorous unbiased method for removing them, this is the data that was then subject to the fit process. On fitting it, a residual (equal to data minus the best fit) was recovered with the following form:

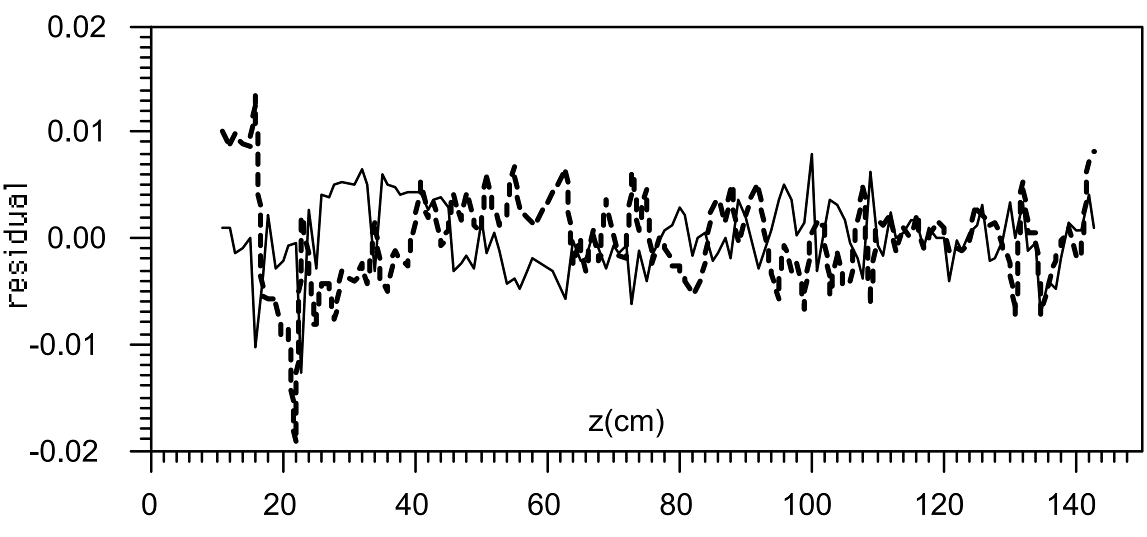

FIGURE 7] The difference (residual) between the measured data and that of the best-fit shows some remaining systematic residuals, plus a random noise. Solid and dashed lines represent the residuals of the in- and out-of-phase parts.

The residuals of Fig 7 show the presence of random noise. Being random and rapidly fluctuating, they are of little importance. The figure also shows the presence of some trends; thus the data have been influenced by uncompensated drifts. The best fit was obtained at a wavenumber approximately 1% below that predicted by the FEM code. This corresponds, if one were to interpret it literally, to a neutral temperature that differs from the actual by 38 degrees F. From a scientific point of view, the field work can be considered a success; much has been learned, and the essential behavior is indeed observed. From a practical point of view, there are several technical issues to be addressed.

CONCLUSIONS

Sources of error and imprecision remain. They may be categorized as measurement errors and reference errors. They can all be solved by straightforward further work.

Measurement errors are due to slop in the laser scan platform and its manual adjustments, and - in the field work - to uncompensated drifts in structural responses. In both cases, an improved scan platform will solve the problem. An automatic and rapid control of laser positioning will eliminate errors due to operator fatigue and manual adjustment imprecisions. Rapid laser scanning will allow field-scans to be conducted while the structure remains unchanged, and/or allow re-calibrations to be automatically conducted, thereby mitigating against irregular changes in structural response.

Reference errors, as illustrated by the not-yet-understood 0.34% intercept seen in the test-bay results, may be due to an imperfectly understood rail profile (this can be compensated by rail profilometry and/or by conducting tests at more than one frequency); it may be due to error in the FEM code that predicted the reference wavenumber (though this is judged to be very unlikely, the matter does need some additional scrutiny before we can be certain) It may be due to some systematic error in the operation of the manual scan platform and its adjustments (this also will be solved by the improved platform)

These errors will have to be addressed before the artificially set goal of accomplishing the required precision with one meter scans can be met. There is every indication that re-setting the goal at accomplishing the stated precision with a two meter scan is meetable at present.

PLANS FOR IMPLEMENTATION

The method is promising, and further work should be conducted. Chief amongst that work's purview should be the design of a better laser platform, followed by a re-visit of laboratory work, and the field work. Scan systems are a well developed technology, see e.g. Parker-Hannifin's Daedel Electromechanical Positioning systems, where a variety of speeds and controls and rigidities and positioning accuracies may be specified. We envision a system that will move rapidly (meter/sec speeds are typical, and accelerations are rapid) between 50 or more specified positions a few cm apart, and take two or three seconds of data at each position - for a total scan time of less than 3 minutes. A manual adjustment to a new height (for greater cost this could be made computer-controlled too, and may well be in a later phase) is then followed by a second set of 50 data points. Automatic computer controlled returns to a specified point will allow regular re-calibrations, should they prove necessary. Position accuracies of 0.2 mm are easily obtained with belt-driven systems and stepper motors; greater positioning accuracy is then obtained by adding a linear encoder (at greater expense ~$2k). Ball screw driven systems, with servo-motor control, are less electronically-noisy (this may be a concern) and more accurate and do not need the linear encoder. Such a system may be preferable. There are several options, and the specifications we will need to set are readily met.

The project extension should also be addressed towards understanding the irregular changes in structural response seen in the field work. To what are they owed? Under what conditions will they not occur? Can they be eliminated? We have a plan to address this matter. Questions to be addressed include: Will their effect be minimizeable by use of a more rapid scanning apparatus that will allow more frequent re-calibrations? Were the changes merely due to shifts in the relatively weak, and jury-rigged, magnetic accelerometer attachment we used there (a commercial magnetic mounting pad is available to replace it with, and is inexpensive.) Were these changes related to the time of day as the rail heated under the strong sun and made and broke contact with fasteners? If so, can that effect be minimized, perhaps by first shaking the rail at high amplitude in order to relax such sites? Would replacing the accelerometer with one or more additional laser vibrometers eliminate the effect, or allow a compensation?

APPENDIX, FINAL PANEL DISCUSSIONS

Members:
D Davis (AAR, TTC), H Newell (NS), A Kish(Volpe), C Barkan (UIUC) and R Weaver(UIUC)

The panel (less A Kish) met by teleconference on Fri Feb 27 and discussed the project, following an outline summarizing this report and prepared in advance.

A Kish and R Weaver discussed the project by telephone Tuesday March 2 following the same outline.

Here is a list of questions and comments that were raised at these discussions:

All are keen on the technique, as the problem of rail force determination is so important, and the proposed method is promising. Many are anxious to see a field prototype.

Weaver continued to note that the requisite precisions, for measured and reference wavenumbers, may be relaxed by the simple expedient of scanning longer ranges, because precision demands drop rapidly with longer scan regions. The panel was of the opinion that keeping the scanned span short, enough so that one needs to remove no more than 3 fasteners, is a good idea. This continues to be the target.

It was asked how would the apparatus be mounted in practice? Currently it is positioned by hand at the rail side, about 18 inches from the rail. We envision an ultimate practical device that would be cantilevered from a high rail vehicle or from a truck parked on the side. Mechanisms would be used to automatically align the scan direction parallel to the axis of the rail, thus assuring a scan line's constant height in field tests. Present project plans envision continued manual installation at each test.

It was pointed out that worn rails have a) a shape very different from AREMA standard and b) lots of head-checks on gage corners, 45 degree hairline cracks of mm depth. If our reference wavenumber is to be obtained in Finite Element predictions based on measured rail profiles and an assumed Young's modulus, will corresponding errors enter? Might this be a serious concern that would demand doing test with longer spans? How accurate is profilometry?

Sensitivity calculations establish that the technique (when conducted with ~ 1 meter scan lengths) will be able to tolerate a 1% error in the effective Young's modulus and a 1/2 % error in radius of gyration (corresponding to about half a mm in head width as measured by profilometry). Experts generally feel that profilometry is conducted well within the stated precision, and Young's modulus is known to the required precision. It was noted, however, that profilometry would need to be conducted at each test site, as profiles can vary from site to site.

The presence of hairline cracks is another matter. Deep or large enough cracks could diminish the effective natural bending rigidity and cause the FEM prediction of reference wavenumber to be in error. RLW offered to estimate the effect. One person thought it unlikely to be an issue.

It was further noted that the proposed "two-frequency" technique which promises to deliver stress and intrinsic rigidity without the need for a highly accurate FEM code, would obviate concerns regarding rail shape, wear and Young's modulus. There would be little or no need for profilometry.

It was widely urged that further tests be conducted on worn, and cracked, rail. This recommendation was accepted. Need for work on rails of very different standard was perceived as less critical.

The erratic shifts seen in the field tests were thought interesting. It was wondered if such shifts are an indication of the state of the structure and if being able to see such shifts could be a fringe benefit.

The panel asked how long scans take. With the present apparatus, they take about half an hour for 100 scan points, at 2 seconds of data at each point. Thus there are about 200 seconds of actual data, and 27 minutes in which the operator is repositioning the laser. In principle, with automatic repositioning, this could be reduced to a total time of about 4 minutes. If electronic and other random noise was sufficiently low (or vibration amplitude was sufficiently high in comparison), the need for 100 points at 2 seconds of data each, could be reduced, further reducing the time needed. The minimum time needed for data taking is likely to be at least a minute per scan. Several scans may be needed. The use of multiple lasers could accelerate the process.

It was appreciated that strain gaging, cutting and rewelding is expensive, but also appreciated that it will be necessary before the technique can be proofed. It was suggested that eventually the project personnel and apparatus should go to TTC and/or Revenue Service mega test sites to do extensive cutting strain gaging and rewelding for such proof tests.

It was also noted that there is an upcoming SRI program on longitudinal stress, and that there may be advantages to coordinating with it.

There was general sense of a preference for the two frequency technique, as opposed to using a (probably huge!) catalog of rail profiles, or a real time FEM run to predict reference wavenumber. The 2 frequency approach, is less dependent on assumptions about rail properties, and does not need profilometry, which could make the test procedure more complicated

It was also suggested that lifting fasteners could change the load, thereby regularizing force distributions, and eliminating extreme values as the rail finds a local equilibrium. On the other hand, removing fasteners is unlikely to change load by large amounts, and would change it only by amounts that could happen anyway as the rail shifts. Of course uplift suffers from the same caveat.

REFERENCES

1] A Kish, S Kalay, A Hazell, J Schoengart, and G Samavedam, "Rail Longitudinal Force Measurement evaluation studies using the track loading vehicle" AREA Bulletin no 742 p315-342 Oct 1993 . Recent conversations with the first author indicate that the uplift technique is reliable for crude assessments of load, but not precise enough for most needs, where measurement of neutral temperature within 5 or 10 degrees F is desired.

2] Livingston, T. and Béliveau, J.G., and Huston, D.R., "Estimation of Axial Load in Prismatic Members Using Flexural Vibrations", Letter to the Editor, Journal of Sound and Vibration, 1995, Vol. 179, No. 5, pp 899-908

Boggs, Thomas P., "Determination of Axial Load and Support Stiffness of Continuous beams by Vibration Analysis", Report No. CE/VPI-ST94/14, Dec. 1994, Virginia Polytechnic Institute and State University (Also a Master's Thesis)

Béliveau, Jean-Guy and Murray, Thomas M., "Lateral Vibration of #115 Rail for Axial Compression up to 100 Kips, Report No. CE/VPI-ST96/03, May 1996, VPI & SU

Béliveau, J.G., Resonant Frequencies of Lateral Vibrations of Rail in Compression, Proceedings, Annual Conference of the Canadian Society for Civil Engineering, Vol. #4, May, 1997, pp. 389-398

Béliveau, Jean-Guy, Murray, Thomas M., and Boggs, Thomas, "Determination of Lateral Stiffness and Axial Load in Rails from Low-Frequency Vibrations", Proceedings 1995 Structural Stability Research Council, Stability Related to Aging, Damaged, & Deteriorated Structures, Kansas City, Mo. March, 1995, pp.129-138

J Béliveau, personal communication.

3] Vesna Damljanovic and Richard L Weaver, "Elastic Waves in Cylindrical waveguides of arbitrary cross section, dispersion relations", in press, J Acoust Soc Am (2004)

4] Vesna Damljanovic and Richard L Weaver, "Elastic Waves in Cylindrical waveguides of arbitrary cross section, forced responses and the inverse problem" in press J Acoust Soc Am (2004)

5] Vesna Damljanovic and Richard L Weaver, "Experiments on the inverse medium problem for harmonic waves in cylindrical waveguides", in press J Sound & Vibr (2004)