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PROJECT
COORDINATOR : CETIM, France

PARTNERS :

LMS International, Belgium
Loughborough University of Technology, Great Britain
Royal Institute of Technology, Sweden
Technical University of Vienna, Austria

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ABSTRACT

The project deals with structure-borne sound intensity (SAI). Three groups of technical problems were addressed which needed further development in order to enable the SAI approach be better exploited in practical applications:

- development of novel SAI measurement techniques,
- extension of the existing SAI computation techniques towards more general application,
- coupling of SAI-type analysis to vibroacoustical approaches of other types.

Referring to these activities, the following results have been obtained: ,

- Codes for the extended SAI computation concerning general excitation and localised damping were developed. Also, an original computation technique based on the experimentally obtained modal data has been verified. The results show critical dependence of the SAI field on the quality of input structural data.
- Development and experimental verification of an in-plane Laser Doppler Velocimetry (LDV)-based sensor for SAI measurement. Very good measurement results have been obtained under laboratory conditions. The hardware developed potentially enables construction of the out-of-plane optical SAI sensor initially planned.
- Investigation of several procedures for Electronic Speckle Pattern Interferometry (ESPI)-based measurements for SAI wholefield reconstruction. In spite of initially encouraging results, the final achievements still lack conclusive results in view of significant influence of speckle noise on results.
- A novel procedure for the measurement of energy flow through resilient mounts has been developed. An error analysis and the associate experimental testing were successfully carried out. The procedure developed stands good chances to become applicable in real conditions.
- The theoretical basis for the adaptation of Principal Component Analysis to SAI measurements has been established. Initial measurements were carried out on simple structures for testing the validity of this approach. The results are encouraging but indicate that the combined SAI/PSA approach has to be used as a method complementary to other methods, not as an independent analysis tool.

1. INTRODUCTION

SILENTA is a multi-partner BRITE project of fundamental research type, which aimed at developing new technology for vibraoacoustical analysis of structures. Three universities, one industrial research center and one industrial company participated as research partners, with a support of several industrial endorsers. The research partners were :

- CETIM - Centre technique des industries mécaniques, Senlis, France (coordinator)
  TUW - Technische Universität Wien, Institut für Allgemeine Physik, Wien, Austria
- LUT - Loughborough University of Technology, Department of Mech. Engineering, Loughborough, UK
- KTH - Royal Institute of Technology, Department of Vehicle Engineering, Stockholm, Sweden
- LMS - Leuven Measurement Systems, Leuven, Belgium

Structure-borne acoustical sound intensity (SAI) is a specific physical quantity which represents flow of sound energy through solid structures. The knowledge of this quantity is useful for specific types of analyses where the visualization of vibroacoustical energy flow across the examined structure has to be established. Its vectorial nature allows for:

- localisation and quantification of vibration sources
- identification and ranking of different propagation paths of structure-borne vibration.

Within the project the development of new SAI techniques and the improvement of the existing ones has been carried out, aiming at the visualization and quantification of vibroacoustical transmission in built-up structures.

Three groups of technical problems were addressed which needed further development in order to enable the SAI approach be better exploited in practical applications:

- development of novel SAI measurement techniques for rapid and accurate experimental work,
- extension of the existing SAI computation techniques towards more general domains of application,
- coupling of SAI-type analysis to vibroacoustical approaches of other types.

The following research activities were targeted:

- extension of the existing SAI computation techniques to the cases of random noise and localised damping; use of measured modal data for SAI post-computation, ,
- development of a method, based on Laser-Doppler Velocimetry (LDV), for point-wise measurement of SAI on objects of arbitrary shape,
- development of a wholefield optical method for measurement of SAI on plane surfaces, based on Electronic Speckle-Pattern Interferometry (ESPI),
- development of a method for measurement of vibroacoustical energy flow through vibration isolators,
- development and validation of SAI methods for vibration source identification using Principal Component Analysis approach.

2. TECHNICAL DESCRIPTION AND RESULTS

2.1 SAI predictive computation techniques

Numerical SAI prediction methods, already conceived before the start of the project, were further improved and validated experimentally. The improvement consists of the addition of random excitation and localised damping in the general computational code with the aim of enlarging the applicability of the code. The developed numerical procedures were validated by the comparison with analytically available solutions for the vibration of flat plates.

2.1.1 Use of modal approach for SAI computation under general excitation conditions

‘The developed computation method is based on the modal approach. Any modal approach is limited to a finite number of modes, typically several tens of modes. This imposes a high frequency limit to the analysis, defined by the values of the eigenfrequencies of the recovered modes. In the usable lower frequency range, the’ influence of non-identified higher order modes on the velocity field utilised for SAI computation was found to be negligible. On the contrary, the dynamic stresses due to higher order modes could not be disregarded. Since the number of modes which can be recovered is usually insufficient for a correct determination of SAI, a particular procedure was formulated to account for the missing high-order modes. It consists of adding a specific complex vector to the modes already evaluated, This vector is based on the static field solution, which is released from the modes already taken into account using the property of modal orthogonality.

Figure 1 shows the comparison between the analytical solution obtained using 100 modes and the numerical solution obtained using 13 computed modes to which the developed high-order equivalent mode was added. The divergence of the intensity field around the excitation point is much better represented when the high-order equivalent mode is taken into account.

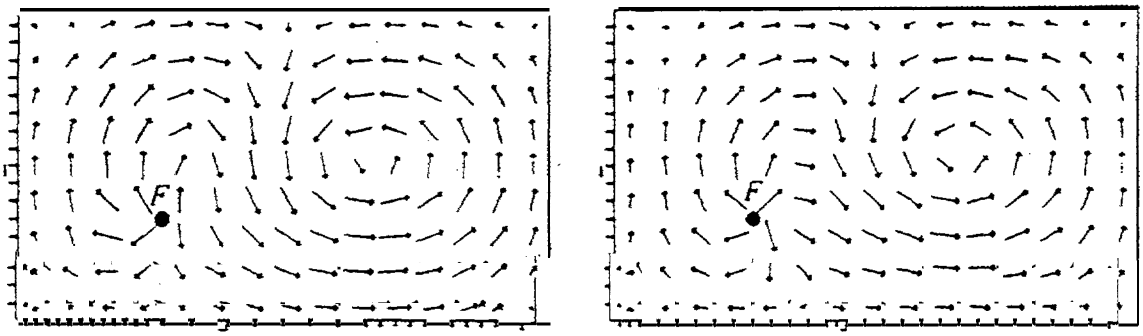


Figure 1: Analytical solution (left) and numerical solution (right). Log scale.

SAI distribution in a structure depends very much on the distribution of structural damping. For a reliable computation of a SAI field, proportional damping used in the FEM approach is not sufficient any more. Thus a new technique of taking the distributed damping into account had to be developed. Here the original untreated structure was considered as being unchanged by the damping treatment, while the effects of the damping layer were taken into account by applying an additional external load, computed through the compatibility interface conditions.

Figure 2 shows the case of a flat plate with and without a partially applied damping layer. The SAI field can be seen to change significantly around the damped area, converging partially towards the damping layer.

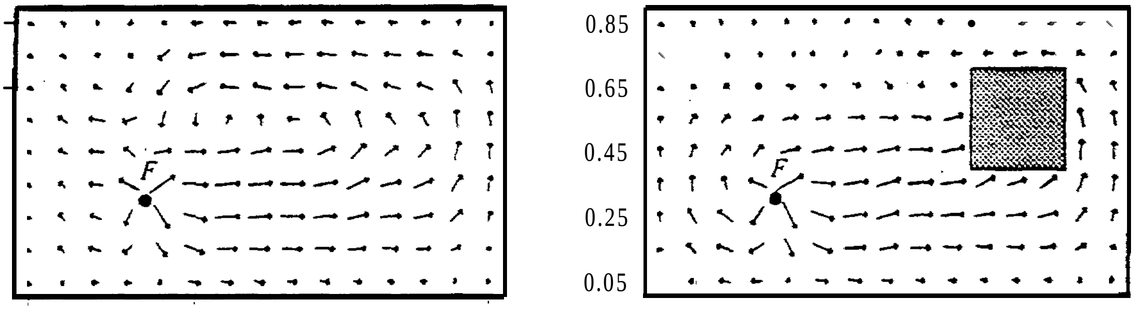


Figure 2: SAI field across plate : left - no damping, right - damping added (dark zone) Log scale

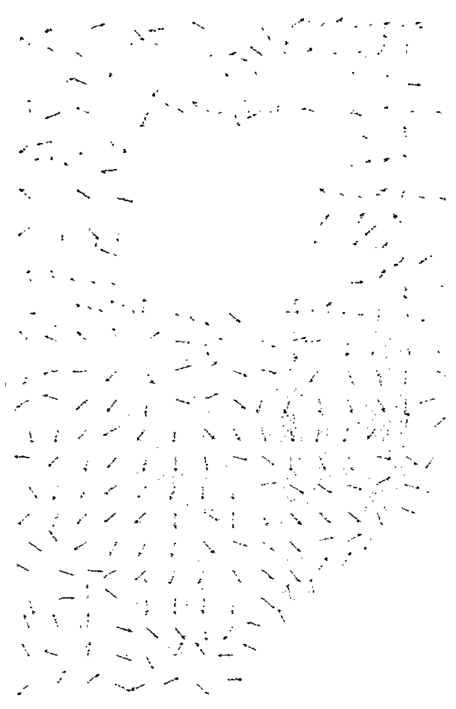


Figure 3: SAI field across the experimental structure (log. scale).

The predictive approach developed was finally tested experimentally. The first attempt ever of using *measured* normal modes in order to evaluate the structural intensity field in the built-up structures has been done within this project using a numerical re-construction of the SAI field from measurement data.

To this end, an experimental structure has been produced. Material properties of this structure - density, dynamic Young's modulus, loss factor and Poisson's ratio - were identified experimentally. The modal response was then measured in an array of points across the structure. These measurement results, obtained at KTH were then transferred to CETIM, where the computation of the SAI map across the structure was carried out using the experimental modal data provided, Fig.3.

The power injected into the structure by a shaker was then evaluated in two different ways: directly, by the measurements of the force and the velocity of the excitation point, and indirectly, by the integration of structural intensity, Fig. 4.

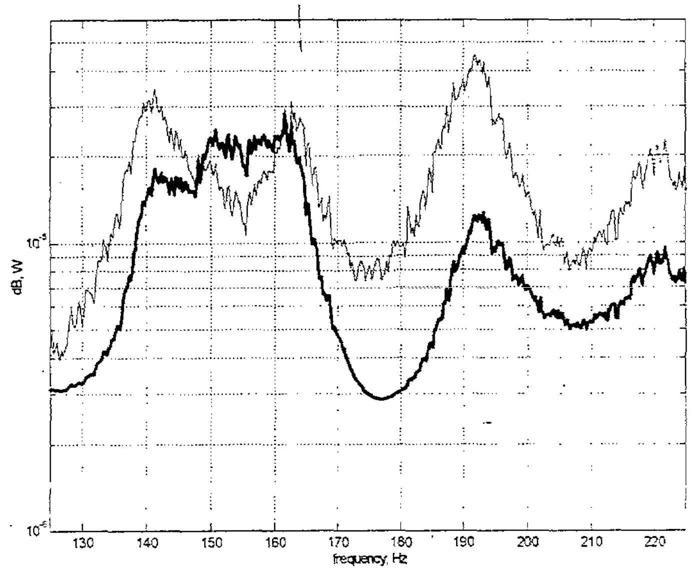


Figure 4: Input power into the plate. Thin line - direct, thick line - SAI integrated

The agreement between the two results could not be considered as satisfying. Some inconsistencies were found in the SAI maps near the plate boundaries, arising from an insufficient representation of higher-order spatial derivatives obtained from the applied finite-difference computation. This calls for a high quality experimental modal analysis to be used in SAI applications.

Finally, the divergence of the intensity field evaluated from *the* measurement data was computed. This is shown on Figure 5, It can be seen that the maximum divergence value is somewhat below the lower left corner of the opening in the structure, just at the position of the excitation force.

Using SAI divergence as a criterion, the location of the excitation was pinpointed, in spite of the fact that the vibration level at the excitation position was well below the maximum levels occurring close to the edges. This has demonstrated the potential use of SAI in diagnostics applications.

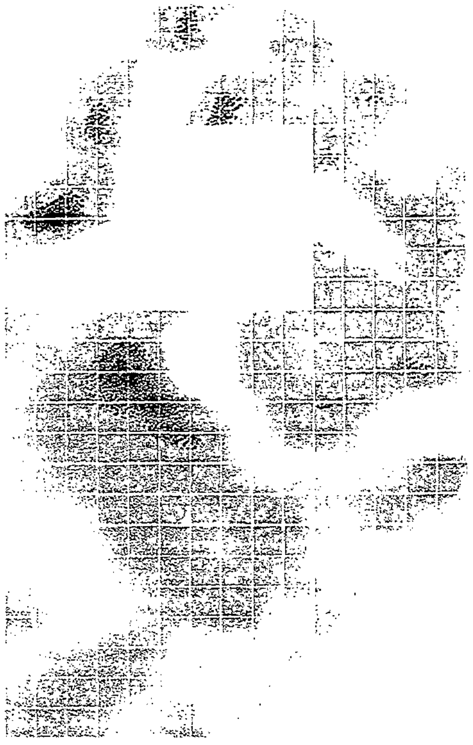


Figure 5: SAI divergence map. The darkest spot clearly indicates the location of the excitation force.

Optical point measurement of SAI

A unique contactless sensor head for the measurement of structural surface intensity was investigated. To this end the Laser Doppler Velocimeter (LDV) principle is utilised. The sensor head consists of several LDVS arranged in a 2-D array. The LDVS simultaneously acquire the vibratory motion at different positions on the measurement surface. The surface SAI vector is then re-constructed from the acquired vibration signals.

The primary measurement quantities, in plane velocity and in-plane strain components, which are necessary for calculating the orthogonal components of the surface SAI vector, are derived from in-plane velocities measured at several close surface positions of the structure analysed. This is done by means of a developed analytical sensor function which is based on finite difference formulation.

Optimisation of LDV'S

The In-Plane LDV consists of an optical head, the signal conditioning electronics and the data acquisition unit. The optical head comprises the laser source, illuminating and receiving optics and the photo diode converting the optical signal into the primary electrical signal. The signal conditioning electronics mainly consists of a phase locked loop (PLL) tracking filter which removes noise from the primary signal. The digitisation of the filtered signal is performed by a frequency counter, The frequency counter data are collected by a computer.

Both the optical LDV head and the signal conditioning electronics had to be optimised in order to obtain high signal quality and make the LDV applicable to the challenging task of surface SAI measurement.

Phase mismatch of the LDV, i.e. a deviation of the measured velocity phase from the true value, has the most severe impact on SAI measurement error, The main source of phase mismatch is the signal conditioning electronics. Band limited white noise with an upper cut-off frequency of 2.5 kHz was for measuring the mismatch between two LDVs. The measured data averaged over 100 single measurements are given in mrad in Fig. 6.

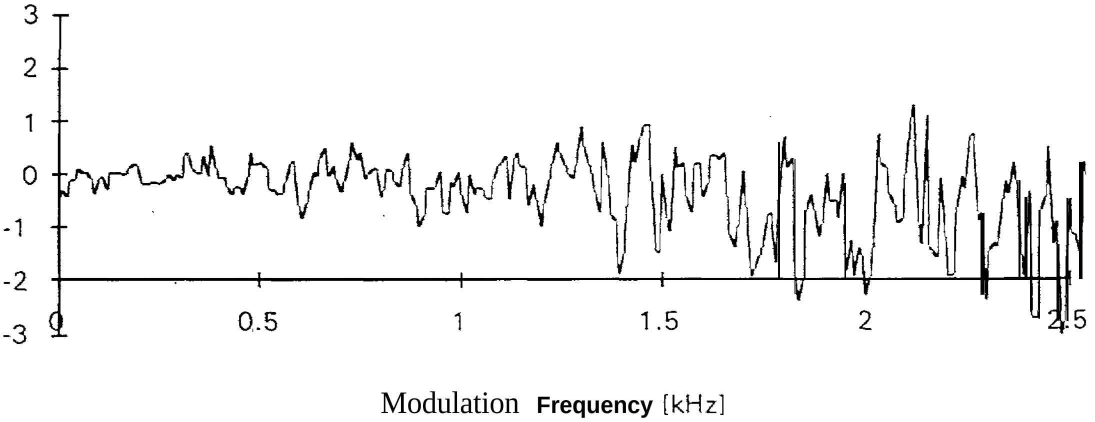


Figure 6: Phase mismatch between two LDV channels. FM depth 100 kHz, 10 dB SNR.

Specifications of a single In-Plane LDV

Max. detectable displacement velocity	0.7 m/s	
Minimum detectable displacement velocity	0.1 mm/s	rms amplitude over 5 kHz bandwidth
Displacement resolution	0.1 µm	for 10 Hz resolution bandwidth
Frequency range for LDV operation	<25 Hz... >20 kHz	
Frequency-Velocity sensitivity	700 Hz/mms^{-1}	
Max. In-Plane Displacement Amplitude	0.5 mm	Displacement amplitude for which a SNR > 10 dB can be maintained, averaged over surface positions delivering SNR >10 dB
Out-of-Plane positioning accuracy requirement	- 2 mm	
Laser power at specimen surface per illuminating beam	7 mW	Wavelength 514 nrn, Collecting aperture 0.03
Out-of-Plane cross sensitivity	$< 10^{-3}$	
In-Plane perpendicular cross sensitivity	$< 10^{-3}$	

The sensor concept was validated by measuring the energy flow in a one-dimensional specimen (PVC tube). In this simple case, only two in-plane LDVS were required for the measurement of SAI along the axis of the specimen. Accordingly, a two-point in-plane SAI surface sensor, based on highly optimised in-plane LDVs, has been set up. ‘

The key specifications of the ‘measurement set-up were evaluated at different frequencies with the specimen excited at both sides by phase-controlled shakers. In this way an arbitrary adjustment of direction and magnitude of energy flow could be achieved under different reverberation conditions.

Figures 6 and 7 give two examples of structural surface intensity measurements on the test specimen using the two-point in-plane sensor. In both cases the specimen has been excited sinusoidally. The distribution of the measured energy flow along the specimen’s axis is shown to change in a monotonous way, as expected, The results at the two extremities agree very well with the direct measurements,

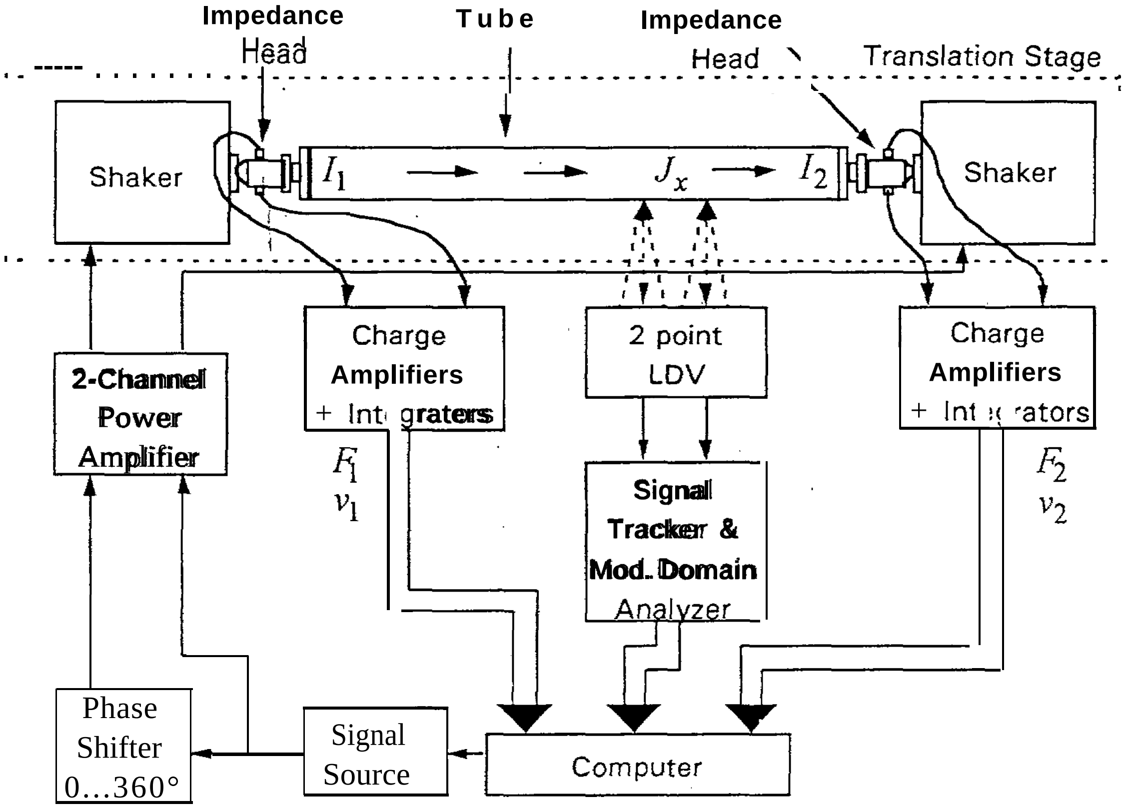


Figure 6:Experimental set-up for testing the 2-point in-plane surface SAI sensor. F_1, F_2 - force signals, v_1, v_2 - velocity signals, I_1 and I_2 - energy flow measured by the impedance head, and J_x - surface SAI measured by the optical sensor.

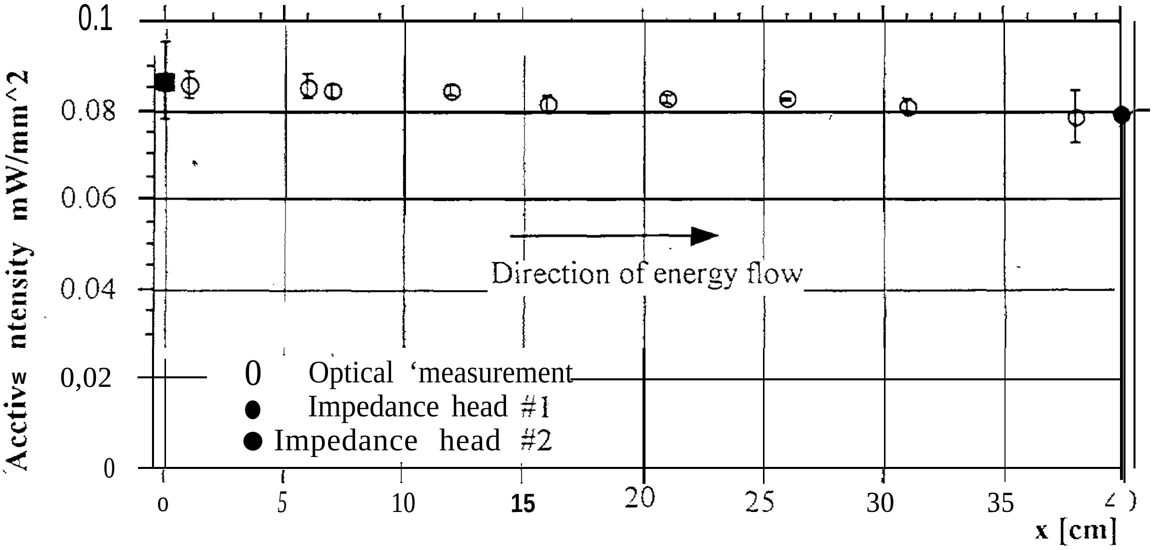


Figure 6: Measured surface SAI over axial position x of a PVC tube vibrating at 200 Hz. Averaging of results over 5 single measurements.

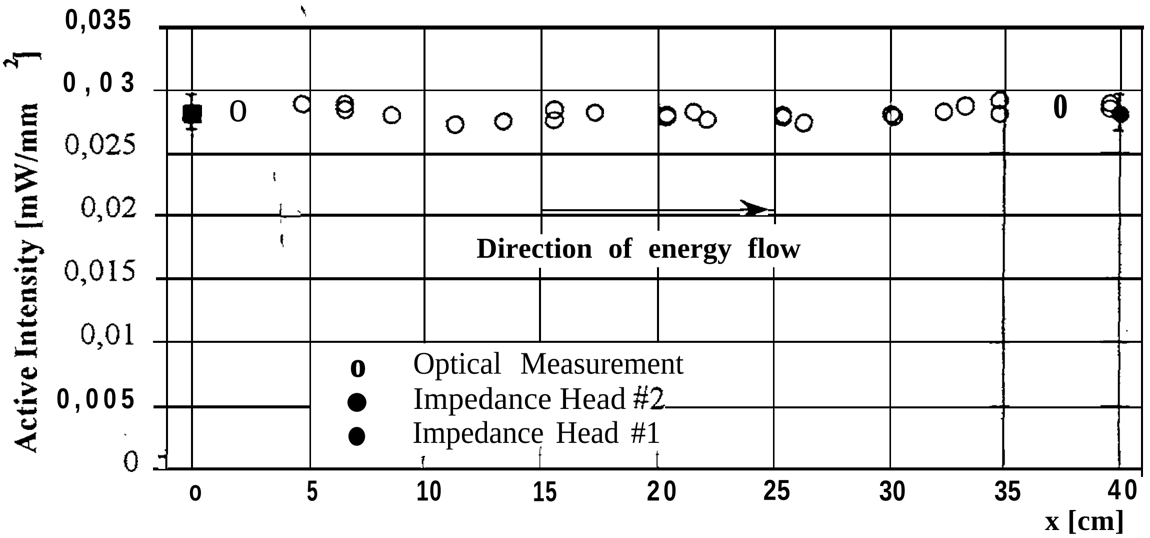


Figure 7: Measured surface SAI over axial position x of a PVC tube vibrating at 750 H... Averaging of results over 5 single measurements.

One-dimensional In-plane Structural Surface Intensity Sensor Specification: Overview

Minimum detectable strain	0..5 µstrains	rms amplitude over 5 kHz bandwidth
Typ. reproducibility of strain	3 %	at 500 Hz vibration frequency
Frequency rang-e	<30 Hz >2 kHz	
Minimum detectable surface energy flow density	10 nW/mm^2	over 5 kHz bandwidth
Typ. reproducibility of surface energy flow density	10 %	without averaging
Absolute accuracy of surface energy flow density	29’0	for optimum d/λ (d.. measurement point distance, k... wavelength)

These results show that the resolution which can be achieved using the developed set-up is, by far, better than requested at the start of the project. The accuracy is also higher than needed in acoustical measurements. However, it should be pointed out that the results were obtained in (favorable) laboratory conditions under well a controlled state of vibration. Even so, these very encouraging results clearly illustrate the potential of the point measurement SAI techniques.

2.3 Optical surface measurement of SAI

This analysis concentrated upon the development of wholefield measurement techniques suitable for the determination of SAI. Electronic Speckle Pattern Interferometry (ESPI), a displacement measuring method, provided the data for subsequent calculation of SAI vectors across the measured surface.

Correlation fringes are created when two states of the object surface are superposed to each other, typically a static undeformed state versus a statically or dynamically deformed state. It is necessary to transfer the object image formed at the CCD-TV camera image plane into a TV-frame store. Each subsequent image from the CCD-TV camera is electronically subtracted from the stored reference and filtered, resulting in correlation fringes being displayed on the TV monitor at a rate of 25 Hz. Consequently changes of object state may be instantly recognised in terms of changing fringe patterns.

Two approaches were considered:

- out-of-plane analysis, suitable for plates and shells, the strains being proportional here to the curvature and twist of the surface,
- in-plane analysis, suitable for any object, relying on the general proportionality between the strains and the gradients of in-plane displacement.

An additional technique known as “shear interferometry" was examined relative to each of the two approaches. Using this technique, correlation interferon-ams can be created by splitting the object wavefront into two components, shifting one with respect to the other by a small lateral distance (known as the lateral shear) and interfering the two speckle wavefronts at the image plane of the CCD-TV camera. In this way the first order *spatial* derivatives of the measured quantity can be obtained in the direction of shear. This potentially interesting concept aimed at a more straightforward strain detection had to be abandoned due to poor resolution of fringe data for typical vibration levels.

2.3.1 Out-of-plane analysis

The SAI requirements for out-of-plane analysis are flexural strain, which requires the double spatial differentiation of the displacement data, and surface velocity, which requires multiple interferograms and accurate synchronisation of the pulsed laser. Wholefield out-of-plane ESPI was used to measure two surface displacements, from which wholefield out-of-plane velocity values were calculated, Flexural strain data could be obtained via the double differentiation of the displacement data.

The object surface is illuminated with pulsed laser light, while a smooth reference beam is introduced onto the face plate of the CCD-TV camera, A novel carrier based technique was developed which was designed to be integrated with the pulsed ESPI interferometers. This was based around a Pockel Cel 1, introduced into the reference arm of the interferometer and synchronised to the laser repetition rate. The additional interferometer optics created horizontally or vertically orientated carrier fringes which were subsequently modulated by the surface displacement. Processing of the distorted modulated by the surface displacement. Processing of the distorted carrier fringes in the Fourier domain directly generates a numerical wholefield map of displacement

The target for the experimental part of the analysis was a square clamped steel plate (200mm x 200mm x 1mm) excited by a loudspeaker. A novel carrier based technique was developed, which was designed to be integrated with the pulsed ESPI interferometers. This was based around additional interferometer optics creating carrier fringes which were subsequently modulated by the surface displacement. The carrier based out-of-plane pulsed ESPI interferometer results demonstrated that strain (displacement derivative) and more specifically velocity values could be derived for a plate or membrane structure but with resolution insufficient for SAI work.

Figure 8 shows the instantaneous velocity map across the surface of the plate’ vibrating in one of its resonant modes. It can be seen that speckle noise affects results to a large extent, in spite of a fairly high level of plate vibrations. This type of resolution is obviously not good enough for creating spatial derivatives.

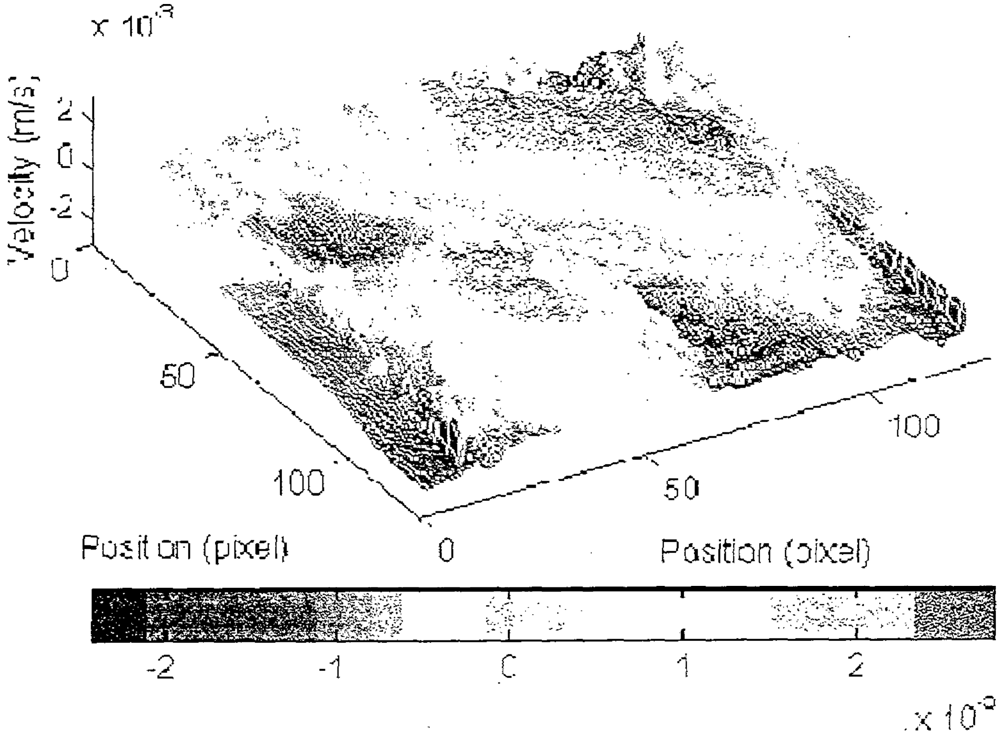


Figure 7: Out of plane velocity field across the plate

2.3.2 In-plane analysis

An in-plane pulsed ESPI interferometer was designed which also included the Pockel Cell optics in one of the illumination legs. Knowing the geometry of the structure and the synchronisation parameters of the pulsed laser with respect to the object motion, the wholefield in-plane strain and velocity values could be calculated for several data sets.

Wholefield in-plane ESPI was used to measure one dimensional resonant motion of a flat plate strip (beam). The vertically suspended beam was excited at the top by a shaker and damped at the bottom by sand. In this way a net flow of vibratory energy was created from the top towards the bottom. Strain and velocity results were obtained which allowed the calculation of SAI values for a middle portion of the beam. The IP ESPI optics were verticality orientated, measuring the vertical in-plane displacement component from which the in-plane strain and velocity could be derived, knowing the beam dimensions and laser pulse synchronisation parameters.

Figure 8 shows the carrier fringe interferogram and the in-plane displacement wrapped phase fringes at the measured surface.

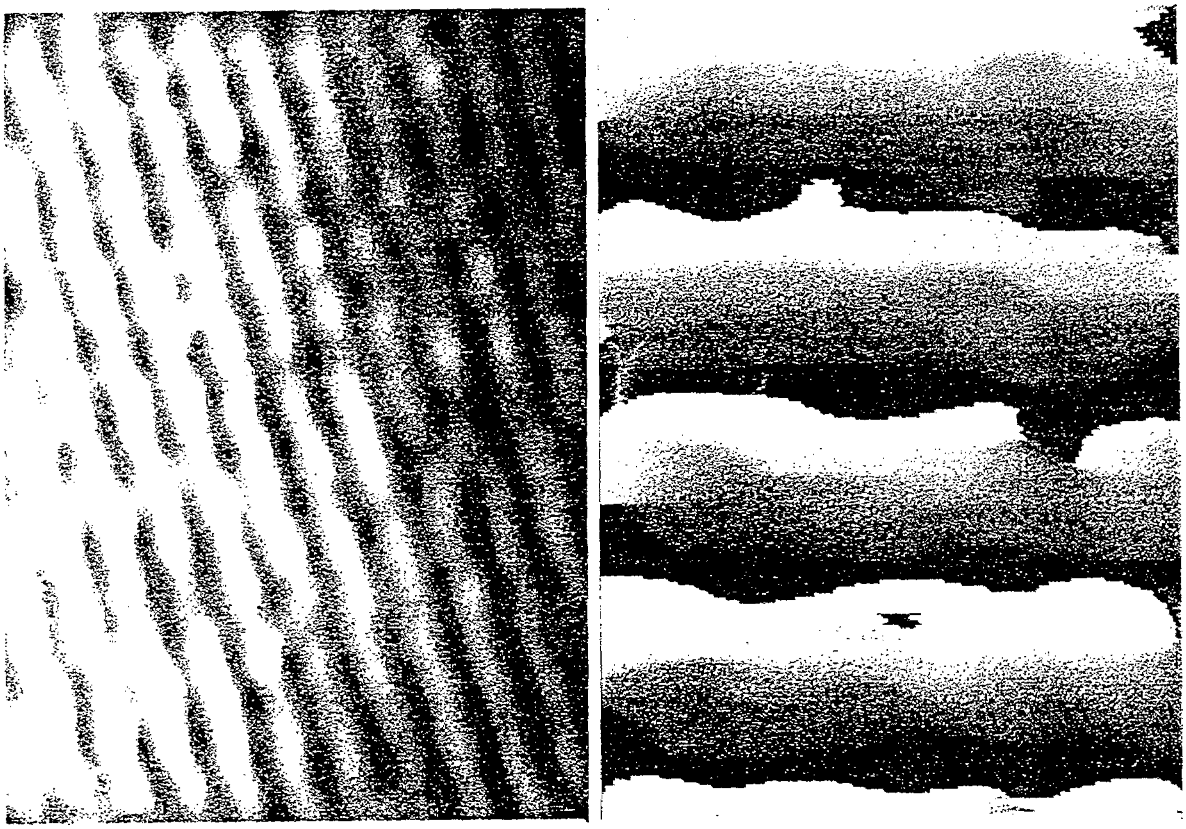


Figure 8: left - Fourier filtered carrier fringe interferogram; right - in-plane displacement wrapped phase fringes

Figure 9 shows the set of four SAI results, calibrated in mW/mm^2, each describing a constant flow of energy down the 1 ength of the beam. The variations in values across each result are a function of speckle noise and varying fringe contrast associated with the ESPI techniques, The noise content has distorted the top 10°/0 of each of the plots and these regions may be ignored for this particular analysis.

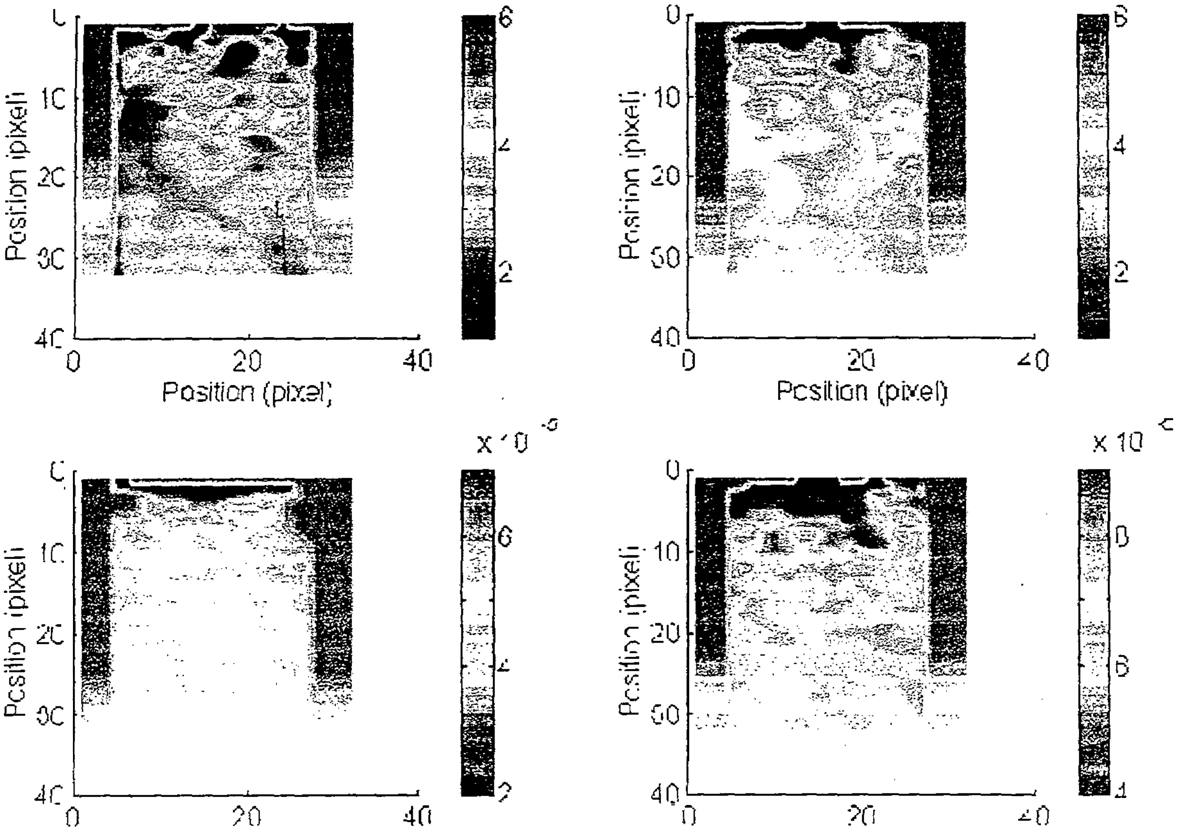


Figure 9: SAI measurement data across the middle portion of the beam.

These wholefield optical results were validated using traditional point source experimental methods. A comparison of the data is shown in the table below.

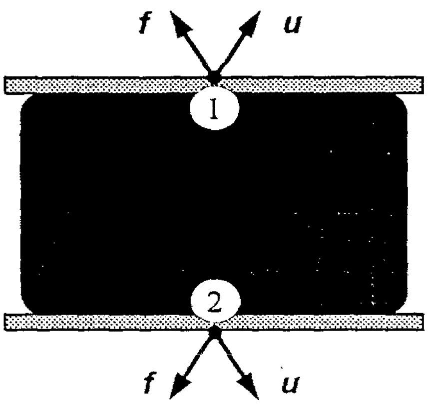
Method	In-plane Velocity (in^{s}1)	In-plane Strain (micro strain)	Intensity (mWmm^{-2})
Wholefield Optical	2.52X1 O-3	49	4,32
Traditional	2.70x10^{-3}	42	4.00
	Out-plane Velocity (in^{s}1)	Force Input (N)	Intensity (mWmm^{-2})
Power Input	0.144	20.3	7.858

Comparison Of traditional and optical measurements

The validation results confirm that the wholefield speckle based technique can correctly measure one dimensional strain and velocity components on a section of the beam. This could potentially extend the measurements to two dimensional cases, the horizontal and vertical velocity and strain components under the condition that further improvement is achieved concerning the spatial resolution of the interferometric fringes and subsequent numerical results.

2.4 Energy flow 'measurement through vibroisolation mountings

In a general case of vibration, each termination point of a resilient mount can vibrate in six degrees of freedom of motion. The resulting dynamic forces and moments at the two interfaces need not to be mutually parallel, neither they need to coincide in direction with the axes of symmetry of the mount if such exist, Figure 10.



The flow of vibration-induced energy through the mount can be obtained as the time-averaged product between the forces (moments) and the corresponding translational (rotational) velocities at the interfaces. A most straightforward way to measure this energy flow would consist in the simultaneous measurement of all the forces and velocities. This way would however be not very practical in situ conditions.

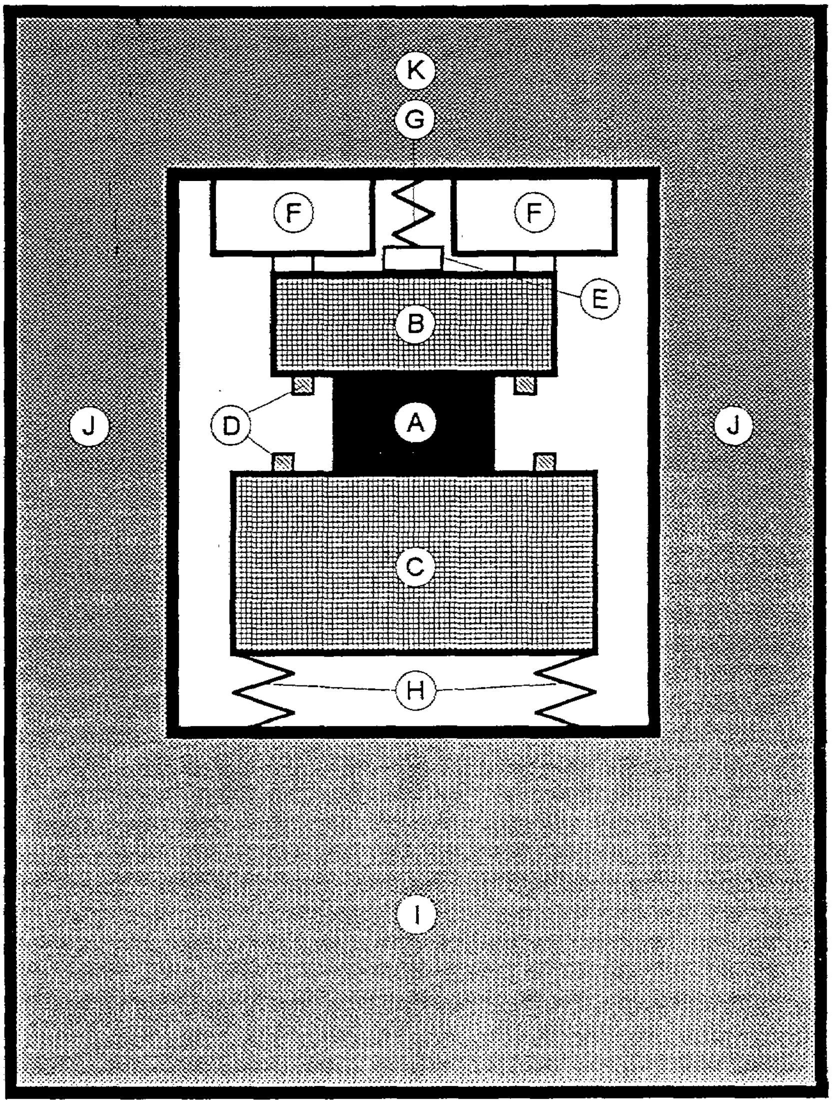
Figure 10: General case of mount vibration

A novel procedure was developed for the measurement of energy flow through an elastic vibration mount. This procedure requires that certain dynamical properties of the mount - the vectorial dynamical stiffness - are first determined, using an appropriate test bench. Once this is done, the energy flow through the mount in situ can be obtained from measurements of vibrations of mount's junctions only.

2.4.1 Measurement of mount properties

The dynamic properties of the mount required for the determination of energy flow are measured by an indirect method. The test rig is depicted in Figure 11, where the measurement of axial dynamic transfer stiffness is shown. The vibration isolator is inserted between upper and lower block. Within the considered frequency range the two blocks behave approximately as rigid masses. The static pre-load is obtained by contracting the upper and lower block via bolts and additional vibration isolators - auxiliary resilient mountings. The upper block is excited by two electro-dynamic vibration generators. The motions of the blocks are measured by piezo electric accelerometers. The measurement set up is embedded in a rigid frame, which is constituted by a crosshead, four strong columns and a heavy and rigid body,

By using an additional mechanisms, the lateral and the rotational dynamic stiffnesses of the mount can be also obtained on this test rig.



A:	*Test Mounting*
B:	*Upper Block*
C:	*Lower Block*
D:	*Piezo Electric* **Accelerometers**
E:	*Force Transducer- Strain Gauge*
F:	*Electro dynamic Vibration Generators*
G:	*Upper Auxiliary Resilient Mountings*
H:	*Lower Auxiliary Resilient Mountings*
I:	*Heavy and Rigid Body*
J:	*Strong Columns*
K:	*Crosshead*

Figure 11: Test rig for measurement of dynamic transfer stiffness of vibration mounts.

2.4.2 Measurement accuracy

The accuracy of measurement can be improved by *several* means:

Improved exciting and block arrangements: a major improvement of the accuracy is achieved by exciting along one basis vector each time.

Stepped sine excitation: to increase the signal-to-noise ratio and to detect possible dynamic non-linearities, stepped sine “excitation is preferable.

Effective mass: to increase the accuracy of the mass sensor for the lower block, the actual effective mass of the lower block should be determined by measurements and taken into account when ‘determining the dynamic stiffness of the mount.

Multiple load method: the accuracy is further improved by identical measurements but different lower blocks. This is a form of multiple load method.

Spatial average of displacements: several symmetric accelerometer positions close to the junction must be used to “average out” motions from other degrees of freedom.

Source correlation technique is used to reduce measurement noise. The output signal from the frequency analyzer is used as source signal.

Error and sensitivity analyses of the developed method were carried out using multi-mount mathematical models of machine-mounts-foundation systems. The main result is the observed high sensitivity of measured energy flow to phase errors. In general, this sensitivity is a common deficiency of power measurement methods, Consequently, the phase of the dynamic stiffness of the vibration mount and the phase of the displacement of the mount junction must be accurately determined.

2.4.3 Results

The developed procedure will work well in the majority of typical cases. The accuracy is increased by using the developed techniques for minimizing the introduced measurement errors. However,. some limitations exist of which the multi point assumption is the most critical. Under this assumption the mount junctions can be represented by six degrees of freedom. This introduces an upper frequency limit, above which the junctions do not behave any more as rigid bodies,

The procedure was tested for a real vibration isolation system. This system included a large hydraulic machine. The dynamic transfer stiffnesses of the mount in all six degrees of freedom were measured for four pre-loads and in the frequency range 100-1000 Hz. The selected vibration mounts were found to exhibit internal anti-resonances within the considered frequency rang-e.

Figure” 12 shows the dynamic stiffness of the mount used in the test (Novibra C 100/54A / rubber hardness A). Figure 13 shows the total vibratory energy flow in axial direction, i.e. the sum of individual flows through all four mounts.

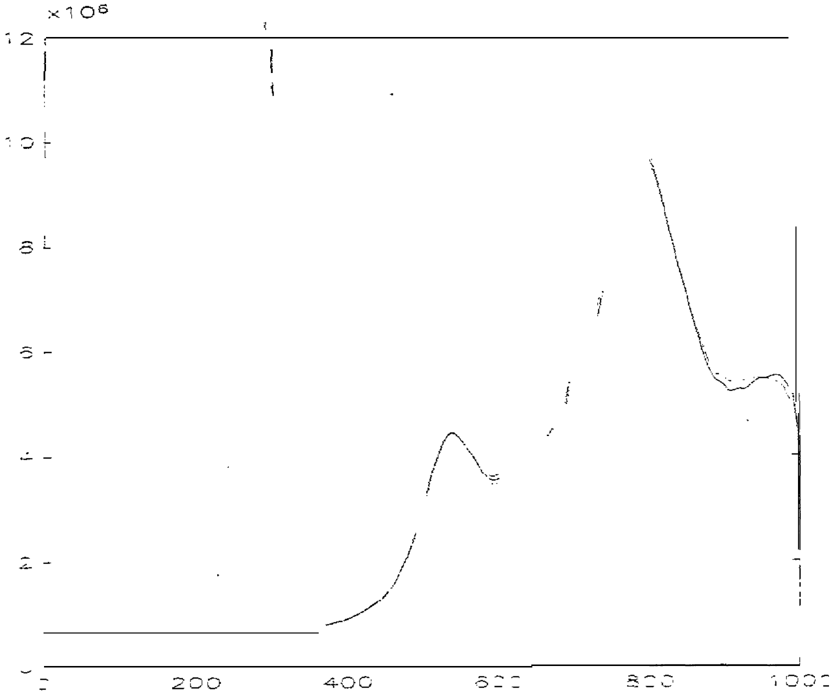
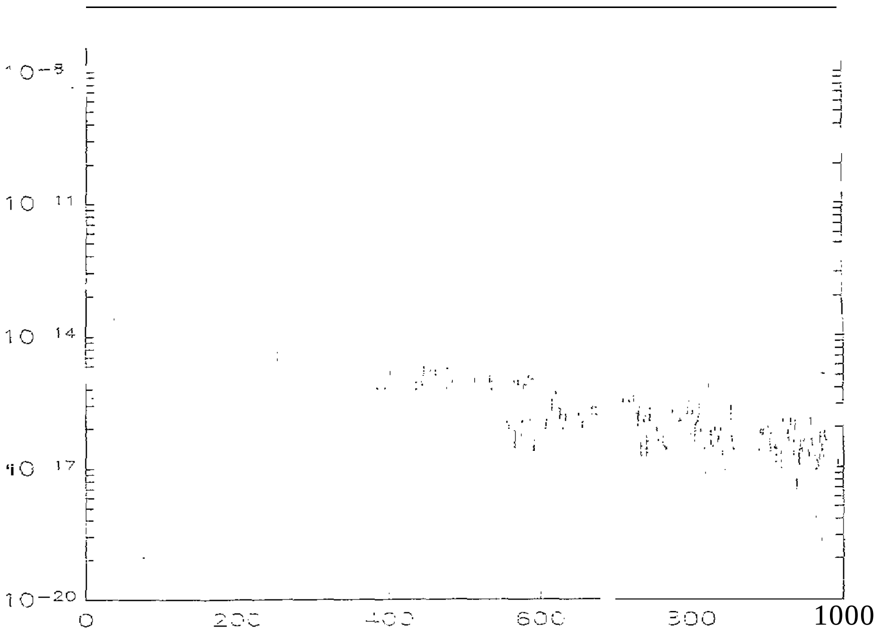


Figure 12: Magnitude of dynamic transfer stiffness in axial direction. Frequency scale in Hz. Preloads: 1375N (blue) 1715N (green) 1970N (yellow) 2170N (red).

Figure 13: Total axial energy flow through the mount system to the foundation. Frequency scale in Hz. Preload: 2170N.



2.5 Use of the SAI approach for source identification

The objective of this part of analysis was to evaluate the applicability of experimental SAI techniques for noise problem identification on mechanical structures, in particular for non-coherent multi-source environments. To this end,. a data reduction process suitable for the evaluation of the sensitivity of vibroacoustical energy transmission to various sources and sinks by field descriptors was examined. A robust and numerically well conditioned approach - the Principal Component Analysis (PCA), based on Singular Value Analysis of a set of reference spectra - was applied to SAI from the theoretical and experimental points of view.

Experimental PCA techniques have been obtained for both beam and plate formulations of SAI measurement. An existing PCA software has been adapted for the acquisition and processing of the data required to obtain SAI distribution on flat plates.

2.5.1 The analysis method

The analysis requires a set of reference points in addition to the target points. Based on the cross-spectral matrix of the reference transducers $[G_{RR}]$, a set of principal reference spectra $[G_{SS}]$ is derived such that:

$$[G_{RR}] = [U_R]\ [G_{SS}]\ [U_R]^H$$

with [t&] a matrix containing in its columns the eigenvectors, while $[G_{SS}]$ is a diagonal matrix containing the positive real eigenvalues in descending order. Using the eigenvector matrix $[U_R]$, the cross power matrix between the target and reference points is the transformed into a "virtual" cross power matrix, relating the target points on the structure to the principal references. This yields a set of referenced cross powers, which become properly scaled and independent RMS complex velocities, coherent with the corresponding reference spectra. These are referred to as principal operating deflection shapes which can be used for calculating the SAI field. Having determined the principal components for a set of chosen points, the virtual coherence functions can be established. Each of these functions determines the degree of dependence between two signals, one real the other virtual.

A large amount of data needed in this approach can be obtained from several acquisition methods. These have been tested to obtain a compromise between acquisition duration and accuracy of results. The chosen method has been implemented to an existing measurement device: a robotized system equipped with two laser vibrometers for non-contact velocity measurement.

In order to evaluate the possibilities of the developed method, an analysis has been done on "academic" structures made of beam and plate assemblies. These structure were very reverberant (with poor dissipation), so some results were difficult to analyse and to interpret. It was found easier to use contour-integrated S AI values to determine the power transmitted to/from a selected area. But the goal of the task - assess the feasibility of the methods and fix measurement parameters - was reached.

A PCA based SAI measurement: example: a plate excited with two independent sources, For each measurement point the principal components of the active intensity can be determined and represented under the form of module and orientation, Figure 14.

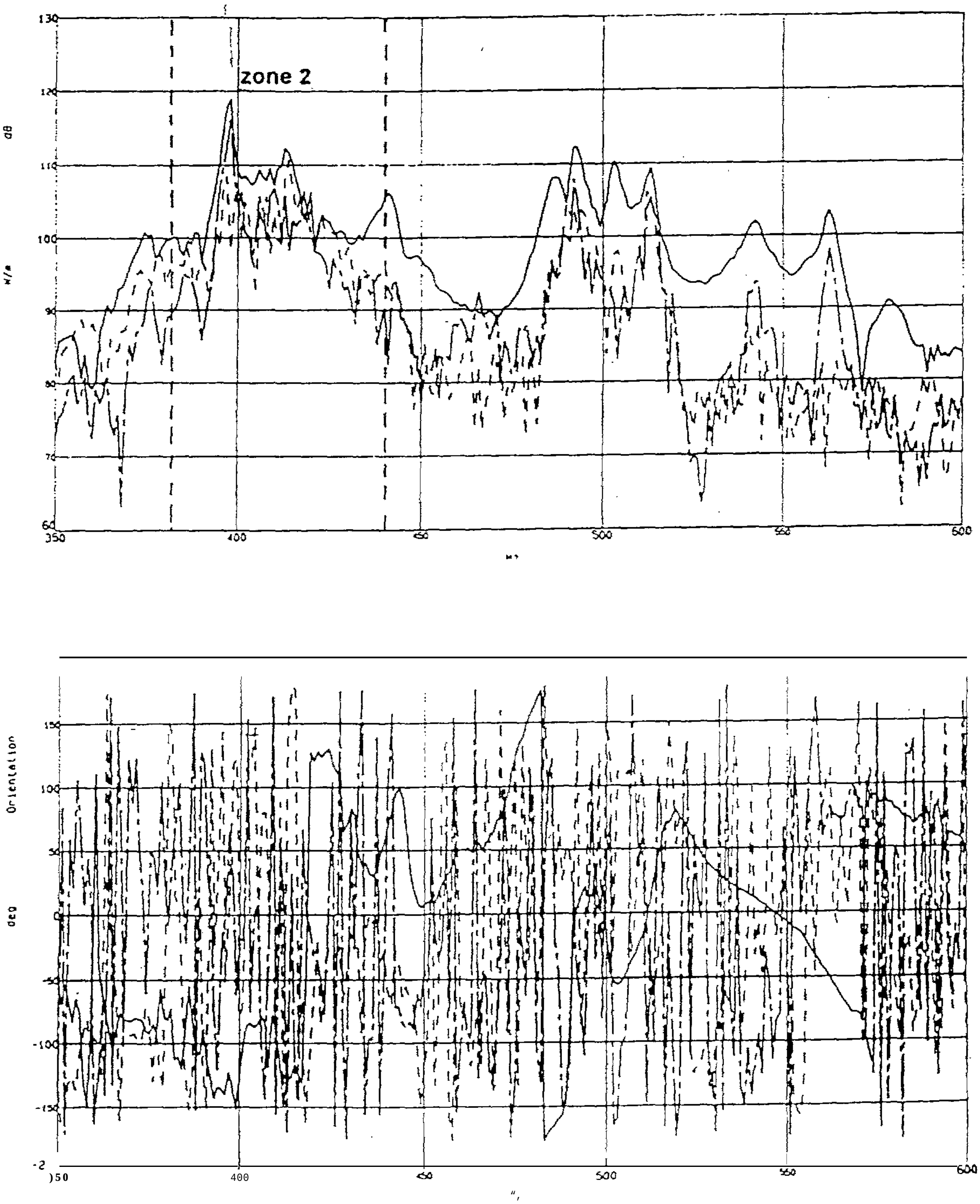


Figure 14: Principal intensity components: top - modulus, bottom - direction

2.5.2 Experimental modelling

An extensive test program has been carried out on a breadboard mechanical structure, representing a simplified car model (subframe-frame-cavity). The test object was excited by three electrodynamic shakers, simulating the engine and two road inputs. The engine was simulated by a narrowband random excitation (250±5 Hz), while two uncorrelated broadband white noise signals (O-5 12 Hz) represented two wheel inputs.

Figure 15 shows the comparison of the contribution of two different references to the SAI field. Different SAI patterns can be observed, indicating the difference in contributions of different principal components to the total field.

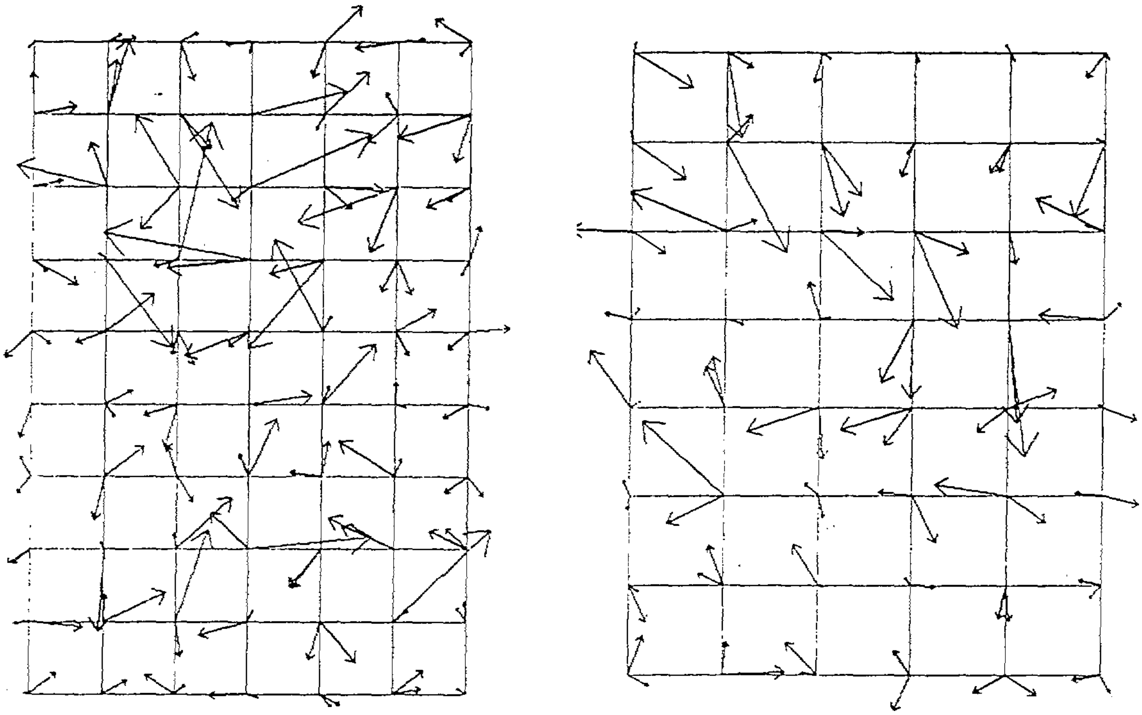


Figure 15: SAI field / second and sixth reference. Left - roof panel, right - floor panel.

3. CONCLUSIONS

Numerical prediction methods, already conceived before the start of the project, were further developed and validated experimentally. The development consists of the addition of random excitation! and localised damping in the general computational code, which has enormously enlarged the applicability of the package for typical industrial needs. The developed procedures were validated by the comparison with analytically available solutions for the vibration of flat plates. Furthermore, the first attempt ever of using *measured* normal modes for evaluating the SAI field in a built-up structure has been successfully accomplished within this project.

A contactless sensor for point measurement of surface SAI was developed. The concept of the sensor head as well as an analysis of errors in measurement was successfully accomplished. Measurements show that the resolution which can be achieved using the developed set-up is by far better than requested at the start of the project. The accuracy is also higher than needed in acoustical measurements. However, it should be pointed out that the results were obtained in (favorable) laboratory conditions under a well controlled state of vibration. Even so, these very encouraging results clearly illustrate the potential of the point measurement SAI techniques. “

ESPI interferometers have provided surface displacement data in the form of correlation fringe patterns, observed in real-time on a TV-monitor. For the needs of SAI measurements wholefield velocity maps have been generated from the displacement data, whilst wholefield strain data have also been derived (knowing the object geometry). A one dimensional case study on a resonant beam has provided in-plane displacement data, which once processed have provided SAI results which agree with traditional measurements. Nonetheless, under the present state-of-the-art the ESPI approach is not yet acceptable for SAI applications in view of significant influence of speckle noise on results.

The developed procedure for measurement of structure borne sound energy flow through vibration mounts works well under typical conditions. It requires knowledge of certain dynamical properties of the mount - the dynamical stiffness - which can be determined using an appropriate test bench. The accuracy is increased by using the developed techniques for minimizing the introduced measurement errors. However, some limitations exist of which the assumption that the mount junctions can be represented by six degrees of freedom is the most critical. This introduces an upper frequency limit to the method.

An existing Principal Component Analysis software has been adapted to SAI in order to obtain the de-composition of the measured SAI field into principal components. A breakthrough was realised in visualizing consistent structure-borne intensity patterns on complex plate structures and in multi-source environment. However, interpretation of the obtained patterns is still cumbersome, and should in principle be based on complementary knowledge of dynamic characteristics and the operational vibroacoustic behaviour of the analysed structure. In essence, this means that the PCA/SAI approach may primarily be a complementary approach, to be used in conjunction with existing technologies (transfer path analysis, operating deflection shape analysis, modal analysis, vibroacoustic coupling analysis, statistical *energy* analysis), rather than being a real alternative for these methods.

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