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# EXPERIMENTAL MEASUREMENT OF STRUCTURAL POWER FLOW ON AN AIRCRAFT FUSELAGE

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## Foreword

This report describes the work performed while visiting the NASA Langley Research Center, Structural Acoustics Division, during the Summer of 1988 and continued following the visit under research Grant, Number NAG-1-685, entitled Use of Energy Accountancy and Power Flow Techniques for Aircraft Noise Transmission". It reports the results for the measurement of power flow (structural intensity) performed on an aircraft fuselage frame. This report covers the period between January 1989 to June 1989. This is the sixth in the series of progress reports under this research grant. During this period two new Master graduate students are working on this research, one addressing the analytical problem of a power flow technique to deal with acoustic excitation including scatter and the second mainly addressing the experimental side to measure power flow on structures.

The author would like to acknowledge the graduate students who participated in this research work, the Department of Ocean Engineering and most important the financial support from the Structural Acoustics Branch of the NASA Langley Research Center.

Submitted by

J.M. Cuschieri
Principal Investigator

## ABSTRACT

An experimental technique is used to measure structural intensity through an aircraft fuselage with an excitation load applied near one of the wing attachment locations. The fuselage is a relatively large structure, requiring a large number of measurement locations to analyze the whole of the structure. For the measurement of structural intensity, multiple point measurements are necessary at every location of interest. A trade off is therefore required between the number of measurement transducers, the mounting of these transducers, and the accuracy of the measurements. Using four transducers mounted on a bakelite platform, structural intensity vectors are measured at locations distributed throughout the fuselage. To minimize the errors associated with using the four transducer technique, the measurement locations are selected to be away from bulkheads and stiffeners. Furthermore, to eliminate phase errors between the four transducer measurements, two set of data are collected for each position, with the orientation of the platform with the four transducers rotated by 180 degrees and an average taken between the two sets of data. The results of these measurements together with a discussion on the suitability of the approach for measuring structural intensity on a real structure are presented in this report.

## INTRODUCTION

Experimental measurements of structural intensity have in the past been performed on generally ideal structures [1,2,3], consisting of either infinite one (beams) or two (plates) dimensional structures, or finite beam structures or alternatively structures with some structural discontinuity but for which a reverberant (resonant) field of vibration was not set up in the area where the structural intensity measurements were performed. The reason for selecting the far field, that is to perform measurements away from any structural discontinuities, or to perform measurements on beam like structures, is that finite difference approximations are used to evaluate the spatial derivatives required for the determination of the structural intensity vectors. A number of closely spaced measurements are necessary to obtain the structural intensity vector at a location on a structure. Simplifying assumptions are therefore required to make these measurements feasible, which lead to restrictions in the application of the measurement procedures.

The measurement of structural intensity near structural discontinuities requires the resolution of all the components [1] of the power flow. In a structure where the structural vibration wavelength to thickness ratio is very large, these power flow components are associated with transverse shear forces, bending moments and twisting moments. Using a finite difference measurement approach, up to thirteen [3] measurement locations (for two dimensional structures) are needed to resolve all of these structural intensity components. This arrangement is difficult to implement in practice, especially with contacting transducers and given the necessary accuracy of the measurements. Furthermore, to resolve all the high order spatial derivatives, the transducers have to be mounted directly on the structure. Moving from one location to another and ensuring accurate location and spacing when mounting the transducers is an enormous task to perform.

Based on these requirements, approximations are typically made with some assumptions regarding the behavior of the structure under test. By assuming that all measurements are performed in the far field away from any form of structural discontinuities, significant simplifications are obtained. For example, the number of measurement locations on plate like structures can be reduced to four by neglecting the near field. Since the four transducers only measure the first spatial derivatives, they can be mounted on a common platform which, provided the influence of the platform is minimal, significantly simplifies moving the transducers from one location to another while retaining their relative locations and separation.

In this report, experimental structural intensity measurements performed on an aircraft fuselage with assumptions regarding the behavior of the structure are reported and discussed. The significance of these results is discussed in light of the measurement assumptions and also in light of the errors that are introduced in the approximations and the measurements. Conclusions are then presented regarding the usefulness of structural intensity measurements. Alternative approaches are discussed with simulated experimental results presented for the case of structural intensity on a flat plate structure.

## BACKGROUND FOR EXPERIMENTAL STRUCTURAL INTENSITY

The structural intensity, or power flow across a line of unit length on the surface of a structure, vibrating mainly in flexure is composed of three components. One component is associated with the shear force and transverse motion of the structure, another component is associated with the bending moment and rotational motion and a third component associated with the twisting moment and the twist rotation. Expressions for these three intensity vector components for a cartesian set of coordinates, in the x-direction are given in equations (1), (2) and (3). The y-direction expressions are similar except for the interchange of x and y.

$$I_S = \left[\frac{\partial w}{\partial t}\right]^* D \left[\frac{\partial^3 w}{\partial x^3} + \frac{\partial^3 w}{\partial x \partial y^2}\right] \qquad 1.$$

$$I_B = -D \left[\frac{\partial^2 w}{\partial x^2} + \nu\frac{\partial^2 w}{\partial y^2}\right] \left[\frac{\partial^2 w}{\partial x \partial t}\right]^* \qquad 2.$$

$$I_T = -D(1 - \nu) \left[\frac{\partial^2 w}{\partial x \partial y}\right] \left[\frac{\partial^2 w}{\partial y \partial t}\right]^* \qquad 3.$$

In equations (1), (2) and (3), w is the transverse displacement, D is the bending stiffness and $\nu$ is poisson's ratio.

To measure completely all three of these structural intensity components, using finite difference approximations for the spatial derivatives, would require two measurements for a first derivative, three measurements for a second derivative and five measurements for a third derivative. A summary of the requirements is shown in figure (1). Thus, to measure all three intensity components for a plate like structure, a total of thirteen measurement locations would be required.

| Component | Terms | Number of Measurement points | |
|---|---|---|---|
| Shear | $\partial^3 w/\partial x^3$ | 5 in line | * * * * * |
| | $\partial^3 w/(\partial x \partial y^2)$ | 3 x 2 | * *<br>* *<br>* * |
| Bending moment | $\partial^2 w/\partial x^2$, $\partial^2 w/\partial y^2$ | 3 in line |   *<br>* * *<br>  * |
| | $\partial w/\partial x$ | 2 in line | * * |
| Twisting moment | $\partial^2 w/\partial x \partial y$ | 2 x 2 | * *<br>* * |
| | $\partial w/\partial y$ | 2 in line | *<br>* |

Total configuration for both x and y directions
13 measurement locations

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    *
  * * *
* * * * *
  * * *
    *
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Figure 1. Required number of measurement locations for finite difference approximations.

It would be difficult to use such an arrangement in practice and therefore approximations are generally used. For measurements in the far field away from point or line sources, power sinks (point or line dampers) and structural discontinuities, the twisting moment component approaches zero [4] and the shear force component equals the sum of the twisting moment and the bending moment components [1]. Therefore the total intensity vector is equal to twice the shear force component. Additionally, by neglecting the exponentially decaying terms (the near field terms), the third order derivatives are equal to the product of the first order derivatives and the square of the wavenumber along the direction of the derivative. Therefore, the shear force component is further simplified and is given by:

$$I_X = 2D \left[\frac{\partial w}{\partial t}\right]^* \left[\frac{\partial w}{\partial x}\right] k^2 \qquad 4.$$

where k is the structure wavenumber and it's the square root of the sum of the squares of the wavenumber components in the x and y directions. The * in equation (4) indicates a complex conjugate.

From equation (4), the structural intensity is represented by the first spatial derivative and can be measured by the use of two transducers in each of the x and y directions (figure 2). The intensity vectors in x and y are then given in terms of the cross spectra between the acceleration measurements by:

$$\text{Intensity}_X = \frac{\sqrt{(EI\rho h)}}{4\Delta\omega^2} \text{Imag}(2S_{21} + S_{23} + S_{24} + S_{31} + S_{41}) \qquad 5.$$

$$\text{Intensity}_Y = \frac{\sqrt{(EI\rho h)}}{4\Delta\omega^2} \text{Imag}(2S_{43} + S_{41} + S_{23} - S_{24} - S_{31}) \qquad 6.$$

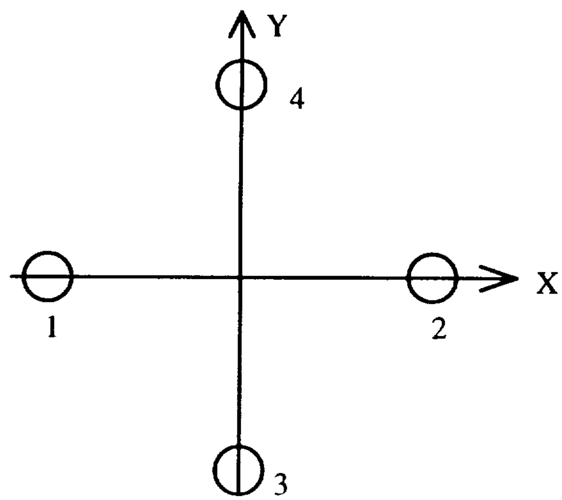


Figure 2. Four Transducer configuration.

where E is the Young's modulus of the structure material, I is the second moment of area, h is the thickness of the structure, $\omega$ is the frequency in radians, $\Delta$ is the separation distance between the transducers and the $S_{ij}$ represent the cross spectra between positions i and j.

The errors that are involved when using this approach to measure structural intensity are of two types. The first type, is associated with the assumptions made in deriving equations (5) and (6), and is due to the nearfield terms and the use of finite differences. The second type is due to errors in measuring the relative amplitude and phase between the four transducers. In general, amplitude errors are very small and are negligible. However, phase errors can be significant since the phase difference of the signal measured by each transducer which represents the propagating component of the vibrational power per unit structure cross section can also be very small. If the phase difference is of the same order of magnitude as the phase errors of the transducer, then the measurements can be totally, in error. Therefore, phase errors need to be compensated for to insure accurate data.

Compensation for the phase errors can be accomplished in either of two ways. One approach would be to measure the phase differences between the output from the transducers when all transducers are subjected to the same in-phase motion. This measured phase difference is then used to calibrate the data after it is acquired. The disadvantage of this method is that in the calibration process, the measurement of the phase differences between the transducers must be very accurate; otherwise more errors are introduced. The second approach would be to acquire, for each measurement location, two data sets with the second data set obtained after the orientation of the transducer array is rotated by 180 degrees (figure 3). The two data sets are averaged such that the phase error between any pair of transducers cancels out, since the measurement phase changes sign while the error phase remains the same. In this way there is no introduction of additional errors due to the calibration accuracy.

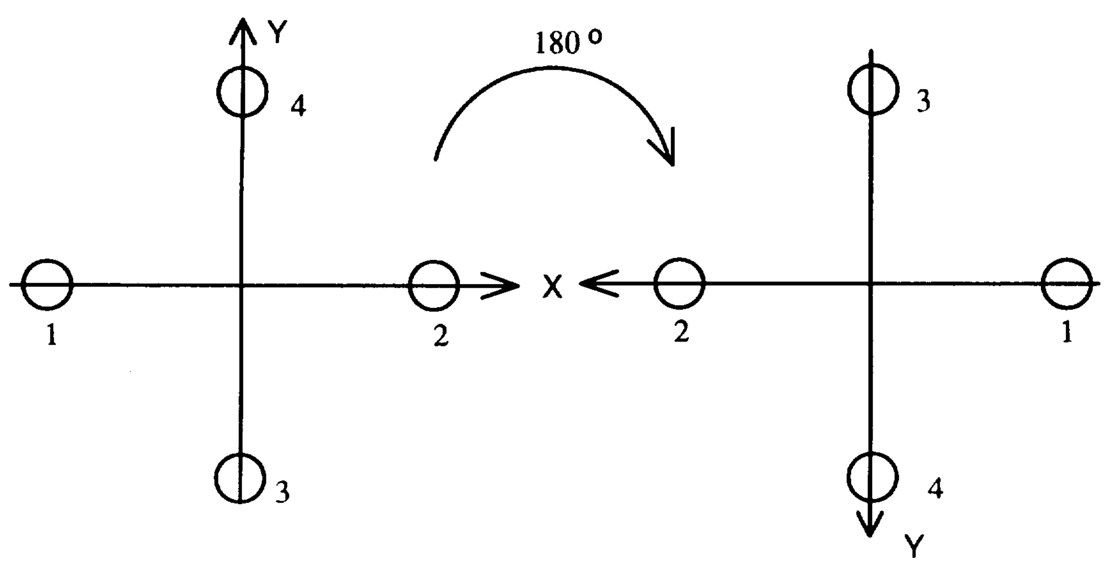


Figure 3. Transducers orientation after rotating by 180°.

In the averaging process to compensate for the phase errors, either of two methods can be used. One method would be to just average the results that are obtained for the x and y components of the intensity vector for the two orientations of the transducer array. Alternatively, an average is taken of the cross spectra between each pair of transducers. In this second method, amplitude errors are assumed to be negligible. The reason for this assumption is that when the orientation of the transducer array is rotated by 180 degrees, the relative phase between transducer pairs that do not lie on the same axis is not reversed. Therefore, the average of the measurements for these transducer pairs do not simply eliminate the phase errors. Since the cross spectra between these transducer pairs are summed as in equations (5) and (6), if amplitude errors are negligible, then in the summing process, the ambiguity in the averaging procedure is eliminated and the result is to remove the phase errors. For transducers that lie on the x or y axis, when the orientation of the transducer array is reversed, the phase errors between these pairs of transducers are eliminated irrespective of the relative amplitude errors.

## EXPERIMENTAL RESULTS ON THE AIRCRAFT FUSELAGE

Using the four transducer array approach outlined in the previous section, structural intensity measurements were performed on a Beechcraft Baron fuselage (figure 4). The four transducers, from which a measure of the first spatial derivative is obtained, were mounted on a bakelite platform (figure 5). The selection of the bakelite was based on the requirements of low mass and high stiffness. The bakelite platform for the transducers had a resonance frequency which was higher than 1 KHz thus ensuring that the independent motion of the transducer platform was not significant compared to that of the fuselage. With this arrangement, the transducer separation was set at 3 cm. The use of the bakelite platform insured that the relative positioning of the transducers was kept constant during the measurements. Additionally, the bakelite platform made moving the transducer array from one location to another on the fuselage, and changing the orientation of the transducer array, easy to implement during the measurement procedure.

With four transducers, measurements could not be performed near structural discontinuities and therefore the locations for the measurements were selected such that these were away from the ribs, stiffeners and bulkheads of the fuselage. At low frequencies only the bulkheads need to be avoided, since the influence of the stiffeners would be to change the overall effective bending stiffness of the fuselage panels. From a previous study [5] it was found that while the thickness of the fuselage panels is (approximately ) 0.5 mm, the effective thickness with the influence of the stringers smeared over the fuselage panels is approximately 5 mm. The effective thickness controls the fuselage panels flexural rigidity. The effective mass was also found to be approximately three times that of the fuselage panels alone [5]. With these effective values for mass and flexural stiffness, the separation distance of the transducers (3 cm) is less than 10% of the flexural wavelength up to a frequency of approximately 600 Hz.

Another consideration which must be taken into account in interpreting the experimental results is that the experimental method for measuring power flow outlined in the previous section is restricted to flat plate type structures where there is no coupling between the wave components in orthogonal directions. This is not the case for cylindrical structures. Therefore, near the nose and tail and near the top and bottom edges of the fuselage, the interpretation of the measurements needs to be done with caution since the structure has some curvature at these locations.

The excitation of the fuselage was by an electromagnetic shaker attached near the wing aft connection location. No special reason for selecting this location except that it represents a typical excitation point of the aircraft. The set up for the excitation and the monitoring of the four transducers is shown in figure (6). No damping measurements were performed on the structure, however from [5], the stated damping loss factor of the fuselage is on the order of 0.03 . This should be sufficiently high to ensure a reasonably low standing wave ratio. As will be shown later no significant resonant peaks were observed in the response of the fuselage.

Figure (7) shows the input vibrational power to the fuselage. As can be observed from this figure the excitation was broad band. Given the size of the fuselage, and the number of measurement locations, single frequency measurements for the determination of the power flow are impractical. Therefore broad band frequency approach was used. The way that the electromagnetic shaker was mounted to the fuselage restricted the input power to frequencies less than 700 Hz. This was acceptable because, using the 3 cm spacing of the transducer array, the maximum frequency without incurring finite difference errors greater than 10% had to be less than approximately 600 Hz. Overall, 109 measurement locations were selected. They were distributed on one side and the top of the fuselage. The measurements did not extend all the way to the rear end of the fuselage and only one set of measurements were performed aft of the bulkhead separating the cabin from the rear baggage compartment.

The measured structural intensity vectors had a large amplitude close to the excitation location but the amplitude decreased rapidly as measurement locations moved away from the excitation location. This is a consequence of the relatively high damping of the fuselage. Therefore in presenting the structural intensity results, the magnitude of the structural intensity vectors are represented by the logarithm relative to a normalizing factor, with the direction of the vector determined from the the linear components in the x and y directions respectively. The results of the measurements for five selected frequencies (68 Hz, 128 Hz, 352 Hz, 400 Hz, 512 Hz) are shown in figures (8) to (12). The "+" on these figures represent the locations on the fuselage at which the measurements were performed.

There is no special reason for selecting these frequencies. The results were obtained for all frequencies in the range 0 to 600 Hz with a frequency resolution of 4 Hz. However, graphically it is difficulties to present the broad band results for a three dimensional structure, and thus results are presented only for the selected frequencies. For each frequency the power vectors for all the measurement locations are overlaid over an outline of the fuselage with the main features indicated. In figures (8) to (12), the cross lines at one end of the intensity vectors indicate the measurement location, that is the vector starts at the cross line location and points away from it giving the structural intensity vector direction and logarithmic magnitude.

From figure (8) it can be observed that at low frequencies the measured structural intensity results are as expected, that is in general they point away from the excitation location and are not affected by the structural discontinuities, except those which restrict the flow of the vibrational power. Such areas with discontinuities are close to the door frame and around the windows of the fuselage. As the frequency is increased (figures 9 and 10) the general pattern remains the same with the power vectors pointing away from the excitation location. However, for these frequencies there is the influence of areas on the structure which are stiffer than other areas such as the forward and mid wing connections. Near these areas the power vectors tend to go around these locations. An exception to the relatively well ordered results is in those areas were the structure has some curvature and also near the forward and aft baggage compartments. In these latter regions the level of structural damping decreases because of no treatment on the fuselage and some errors are introduced because of the high standing wave ratios.

As the frequency is increased further, the relatively well ordered pattern of the structural intensity vectors seems to break down. For the two selected high frequencies, the intensity vectors seem to be pointing in arbitrary directions, some pointing back towards the excitation location and some pointing towards each other. An explanation will be given to some of these results. In the explanation, use will be made of analytical results for structural intensity vectors obtained on an L-shaped plate [2]. Shown in figure (13) are the mode shapes of one of the plates in the L-configuration for some selected frequencies.

Figure (14) shows a comparison between power vectors obtained using, in one instance, the actual calculated values and, in the second instance the values obtained using a finite difference approximation for the derivatives together with the far field assumption. As can be observed from this figure for both modes, there are discrepancies both in the magnitude and orientation of the intensity vectors. The change in the intensity vector orientation is caused by the fact that the finite difference and near field errors are not equal in both the x and y directions. Similar errors in the results are obtained for higher order modes not shown here.

For the higher order modes, the spatial resolution of the intensity vector map also becomes important. As the frequency increases, because of the more complex mode shapes of the structure, the power vector diagrams become increasingly complex. Shown in figure (15) are the structural intensity vector results for two high order modes obtained with different spatial resolution. With low spatial resolution (right section of figure), there apparently are intensity vectors which point towards each other. At first glance this would appear to be contradictory. However, by increasing the spatial resolution one can notice that the vectors are not pointing towards each other, but a complex circulating pattern for the structural intensity is obtained which is controlled by the mode shapes. At locations on the plate of high modal velocity amplitude, which implies areas of high vibrational power dissipation, there is a rotational pattern for the intensity vectors. Vibrational power is mainly dissipated in these areas.

The implications of these results are:

(a) The far field assumption is not valid for the measurement of structural intensity on real structures with boundaries, unless one is only interested in the general trends of the structural intensity and only for relatively low frequencies. The errors in the results can be significant.

(b) For high frequencies, unless the spatial resolution at which structural intensity measurements are performed on a structure is sufficiently high, apparently contradictory results can be obtained.

The only known solution to these problems is to eliminate the far field assumption and increase the spatial resolution. With the elimination of the far field assumption, measurements can be performed anywhere on the fuselage or any type of real structure. The four transducer approach will not produce accurate results for real two dimensional structures.

## CONCLUSION

Structural intensity results can very clearly show the flow of the vibrational power from sources on the structure and how this vibrational power flow around major structural changes. This has been demonstrated in this report by results on an aircraft fuselage. However, when performing structural intensity measurements, some assumptions which in the past have been shown to work in the case of simple structures can produce erroneous results when applied to real structures with discontinuities and boundaries. Simulated experimental results shown in this report for one side of a finite L-shaped plate, show that both the elimination of the far field assumptions and a large number of measurement locations are required to clearly identify the structural intensity patterns. That is, before structural intensity techniques can be used for noise control purposes, or for the understanding of the mechanisms and parameters that control the flow of vibrational power, measurement techniques which can deal with a large number of measurement locations, and which also eliminate the need for far field assumptions are required. The measurement of structural intensity is very critical on the type of assumptions made regarding the measurements, and for real structures some of the assumptions can lead to erroneous results. In the presence of resonant modes and structure boundaries, the far field assumption is invalid and the use of a four accelerometer techniques to measure structural intensity on two dimensional (plate like) structures is inadequate.

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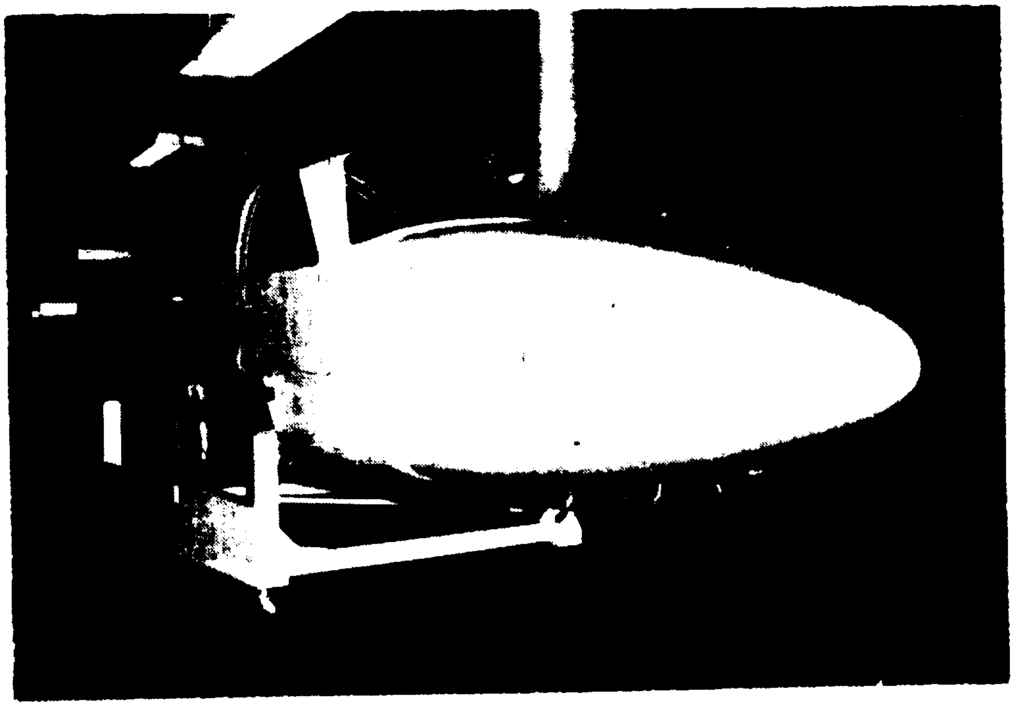


Figure 4. Fuselage of Beechcraft Baron.

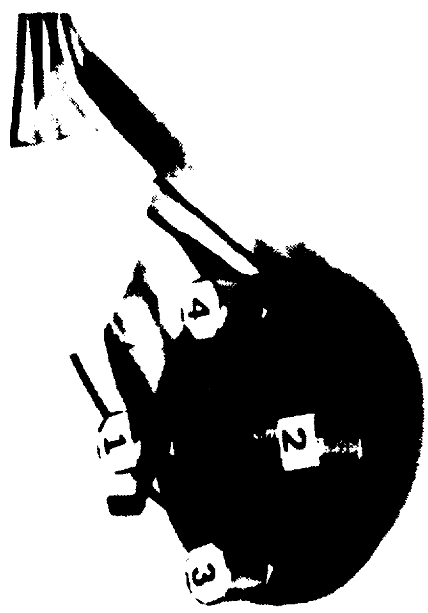



Figure 5. Bakelite accelerometer platform.

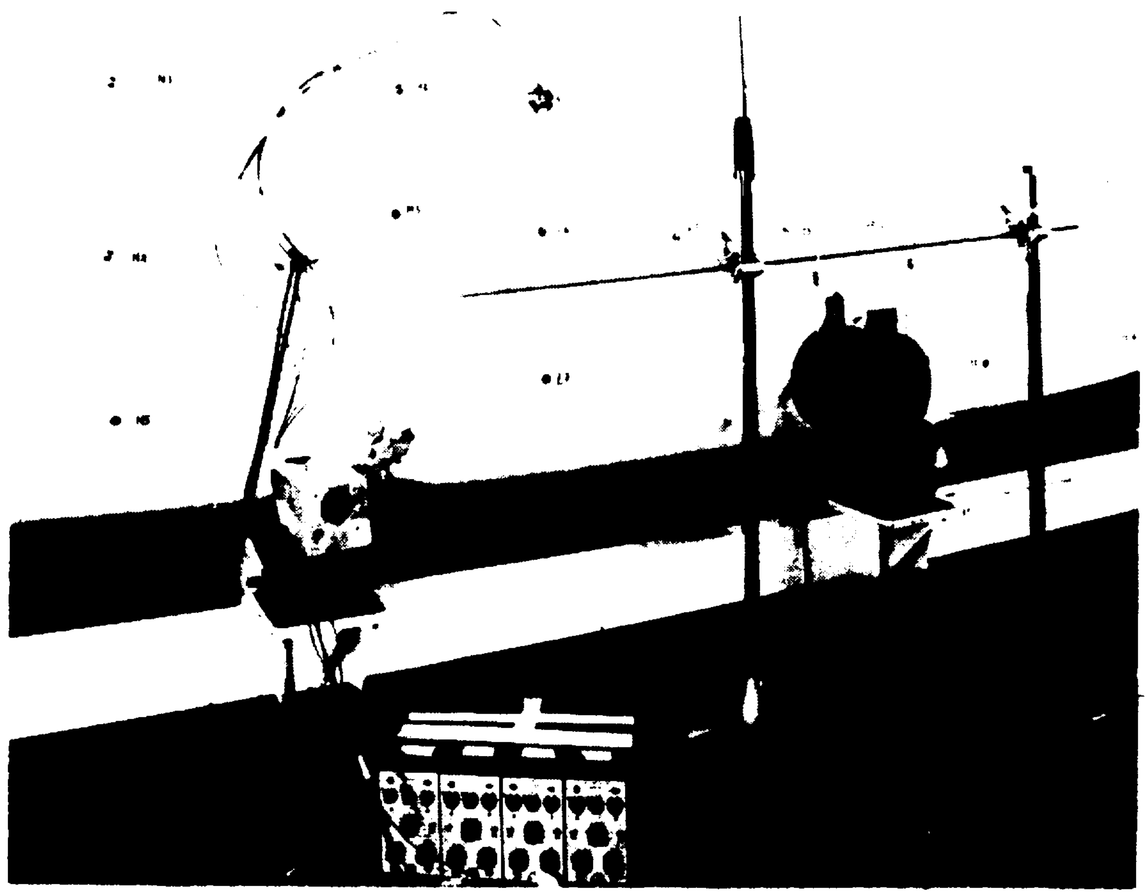


Figure 6. Experimental set up.

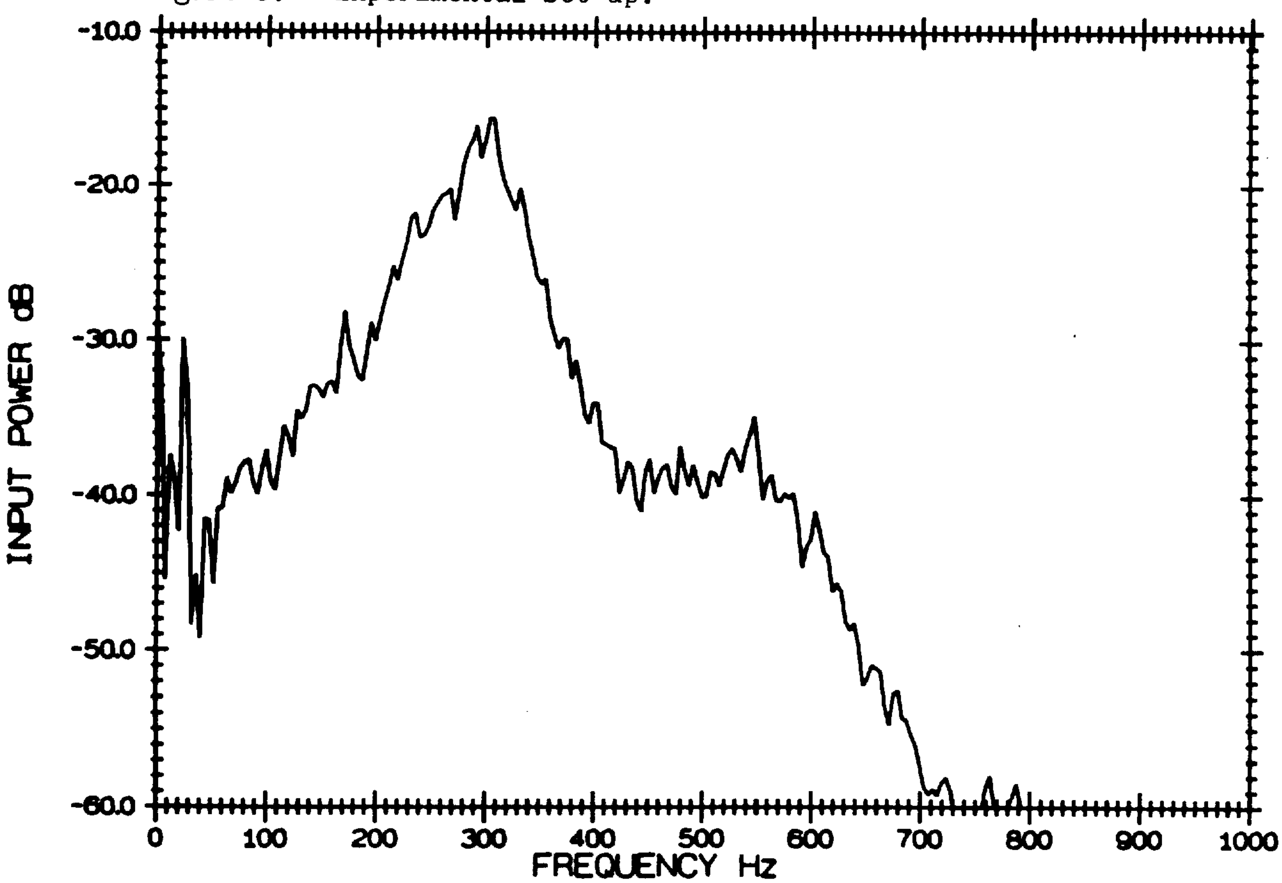



Figure 7. Measured input power spectrum to aircraft fuselage.

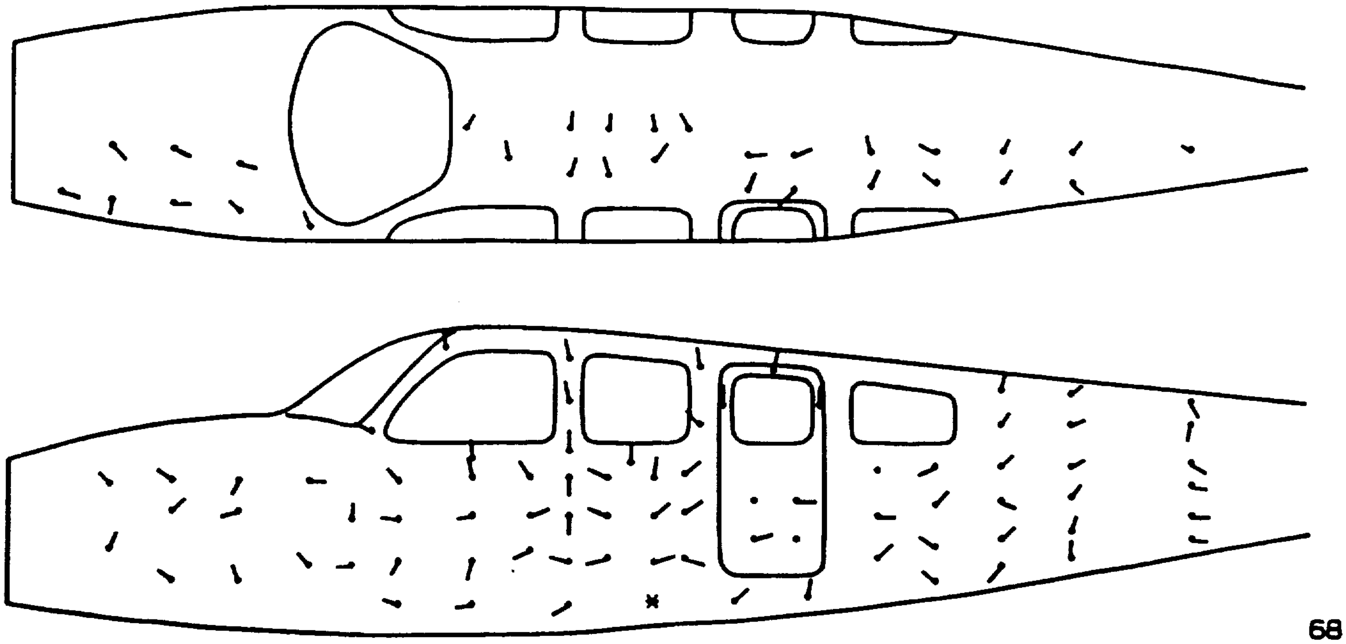



Figure 8. Plot of power vectors for 68 Hz. "+" are measurment locations.

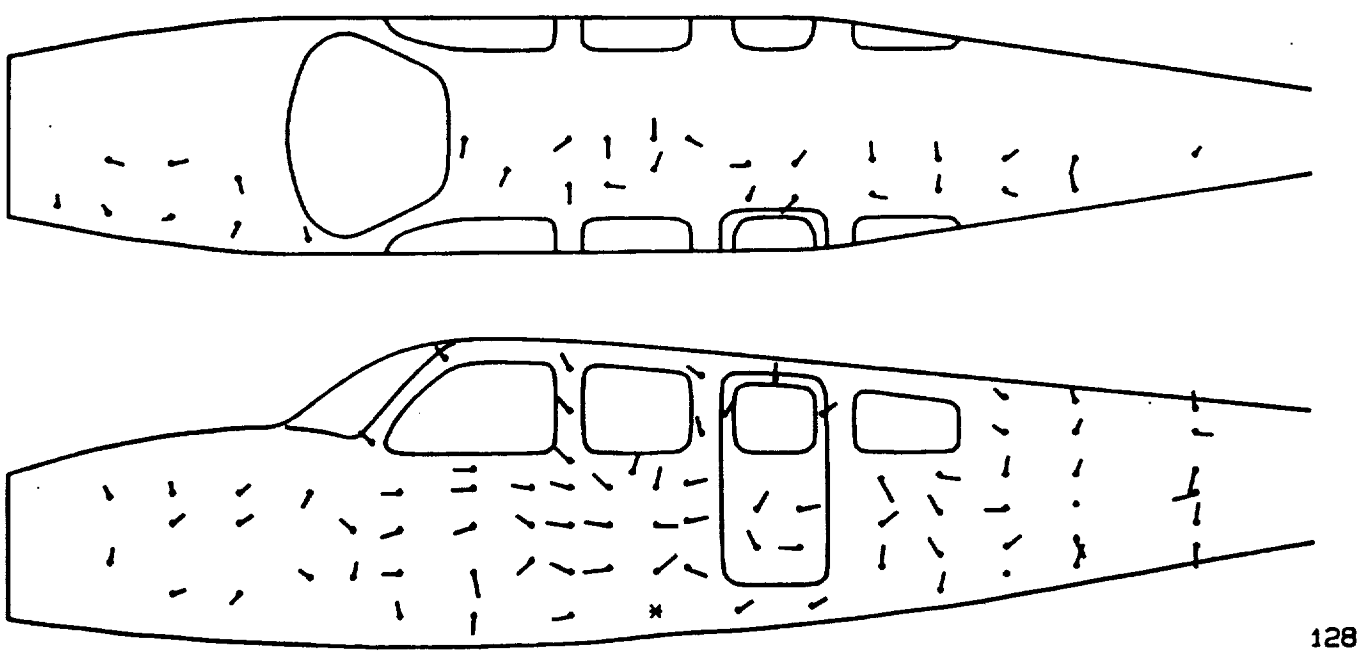



Figure 9. Plot of power vectors for 128 Hz. "+" are measurment locations.

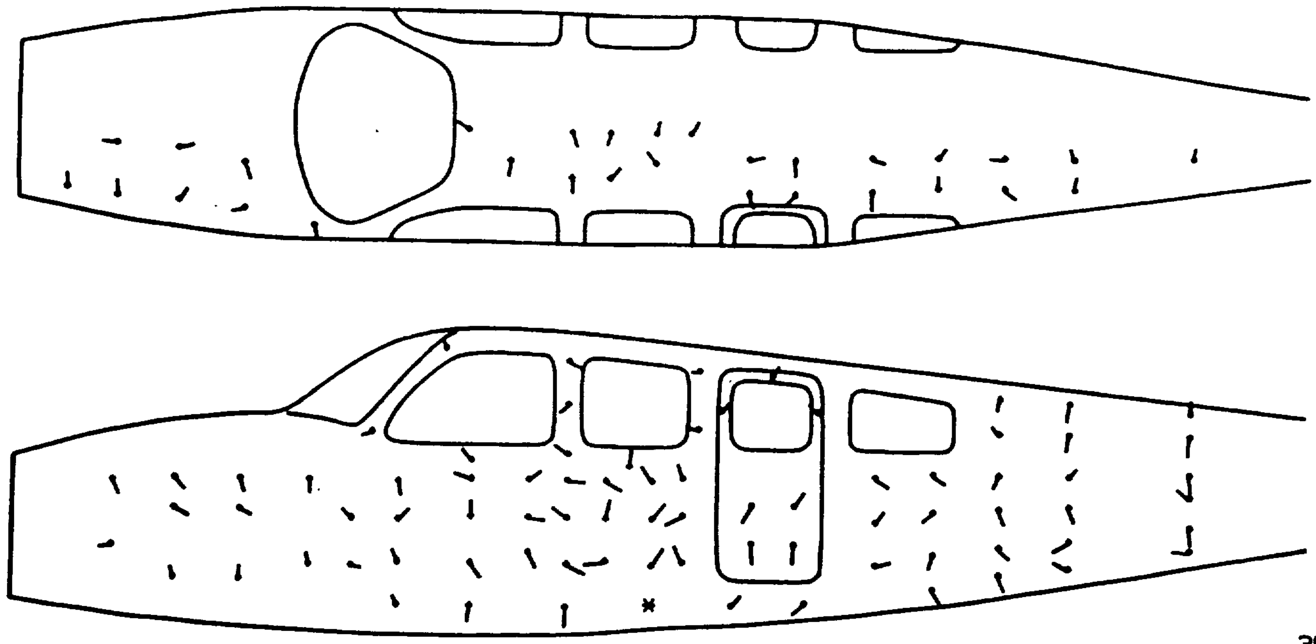



Figure 10. Plot of power vectors for 352 Hz. "+" are measurment locations.

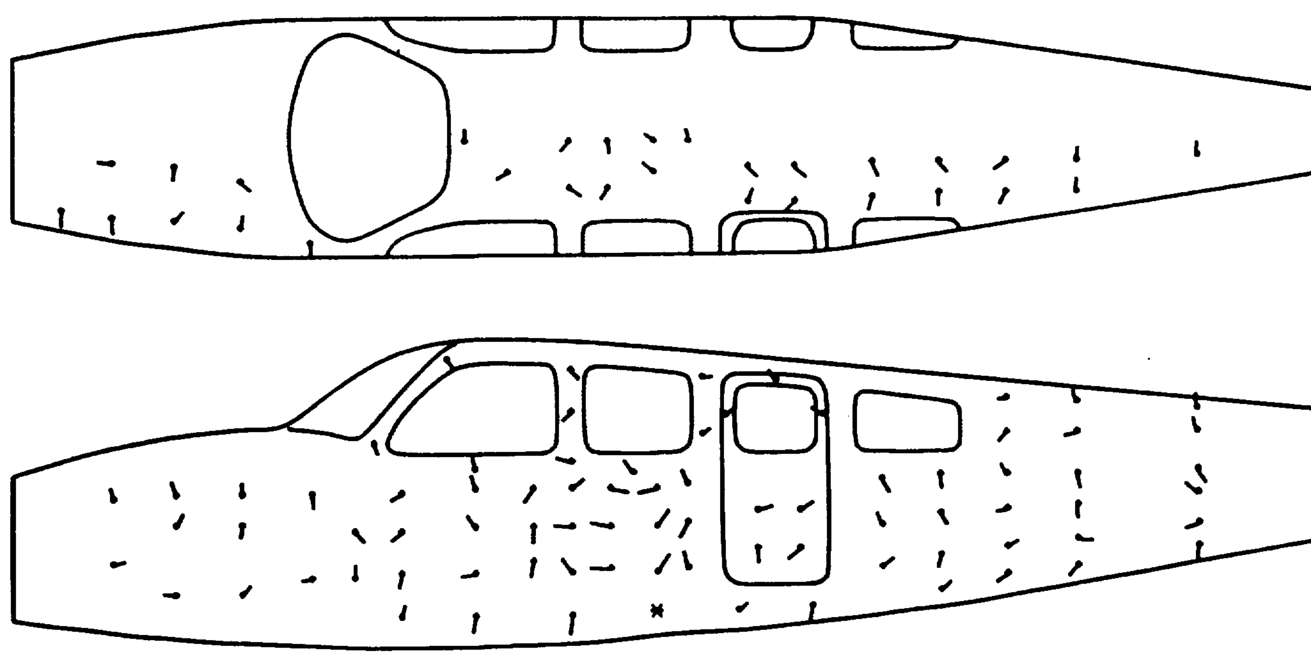



Figure 11. Plot of power vectors for 400 Hz. "+" are measurment locations.

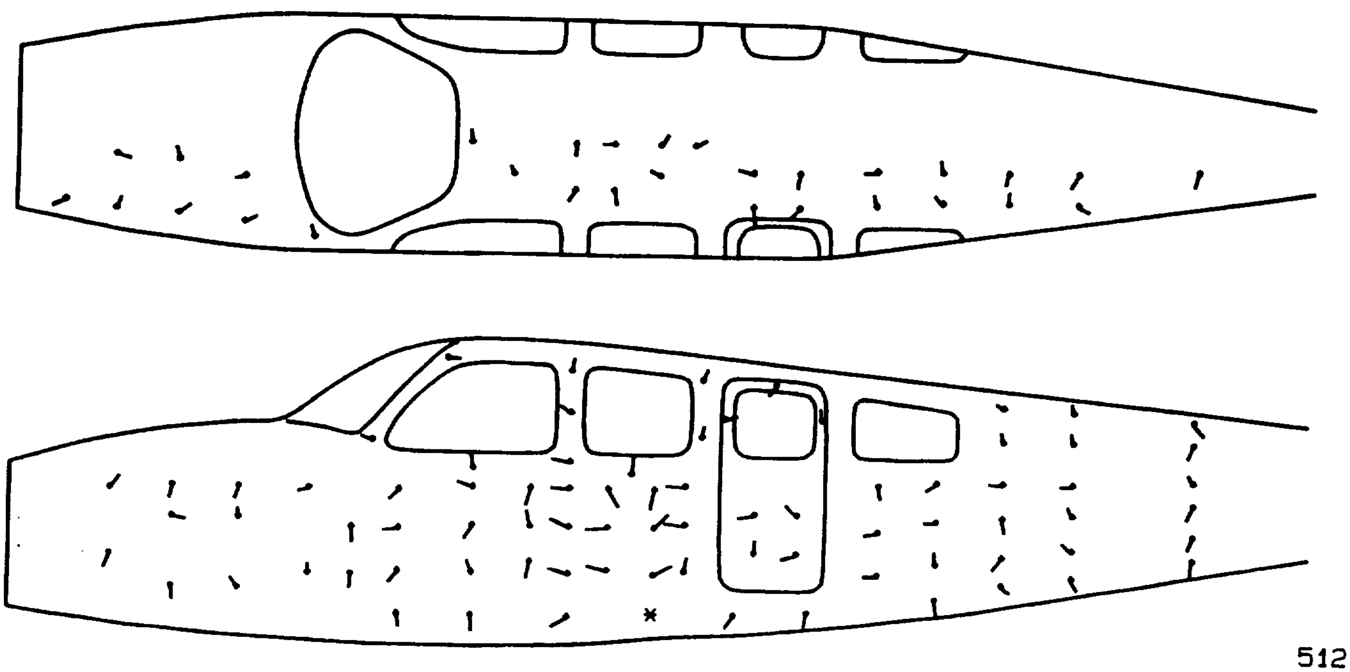



Figure 12. Plot of power vectors for 512 Hz. "+" are measurment locations.

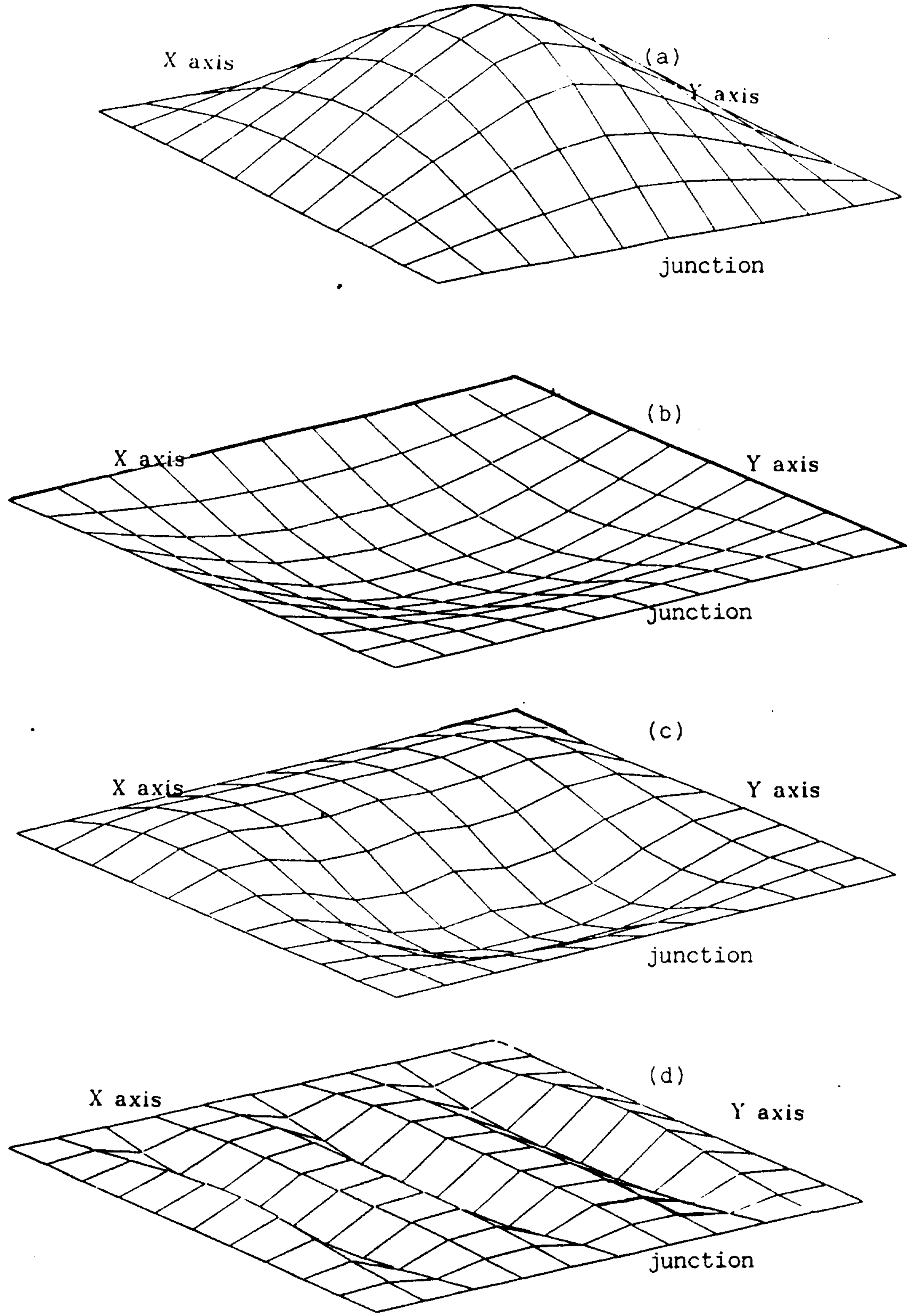
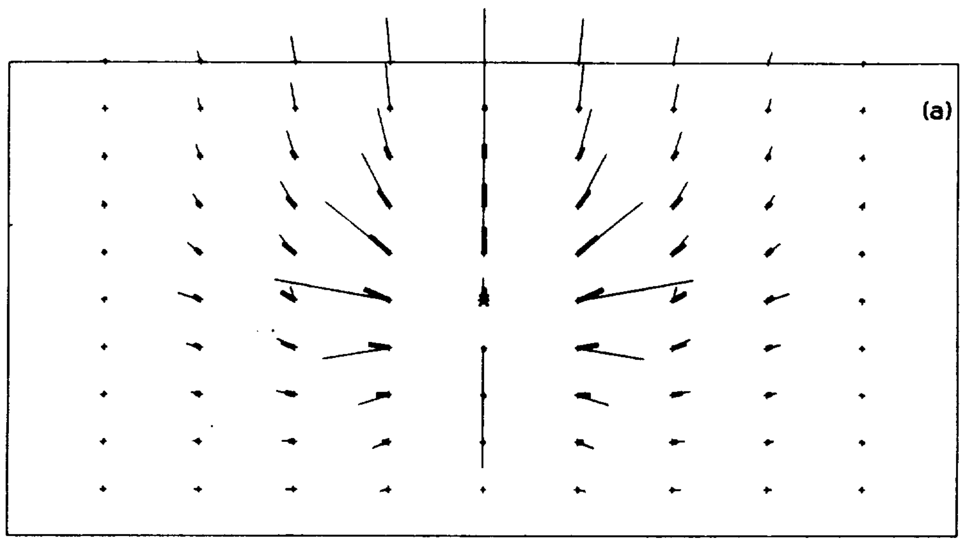



Figure 13. Mode shapes for (a) 78.6 Hz (mode 1); (b) 110 Hz (mode 2); (c) 333 Hz; (d) 841 Hz modes.



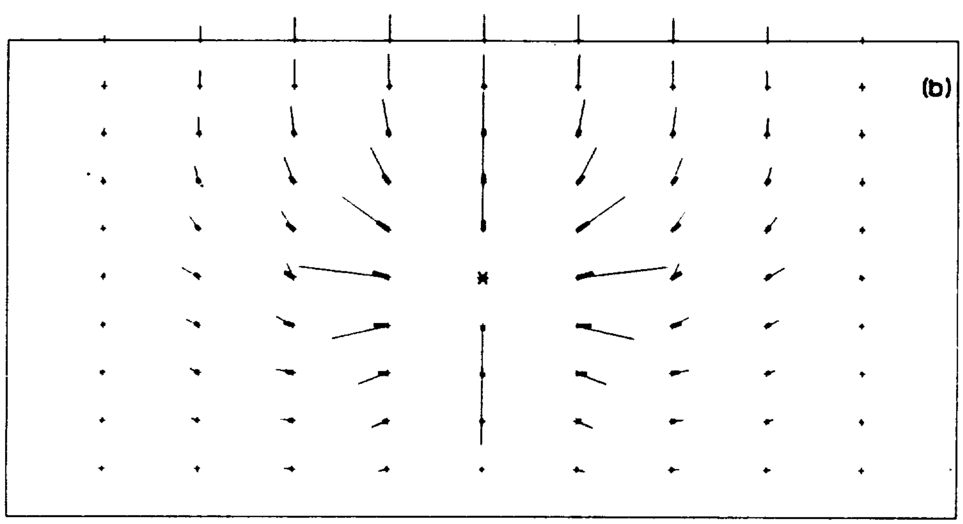




Figure 14. Structural power flow vectors for (a) first and (b) second modes.
——— directly computed intensity vectors;
━━━ vectors computed using finite differences and far field assumption.

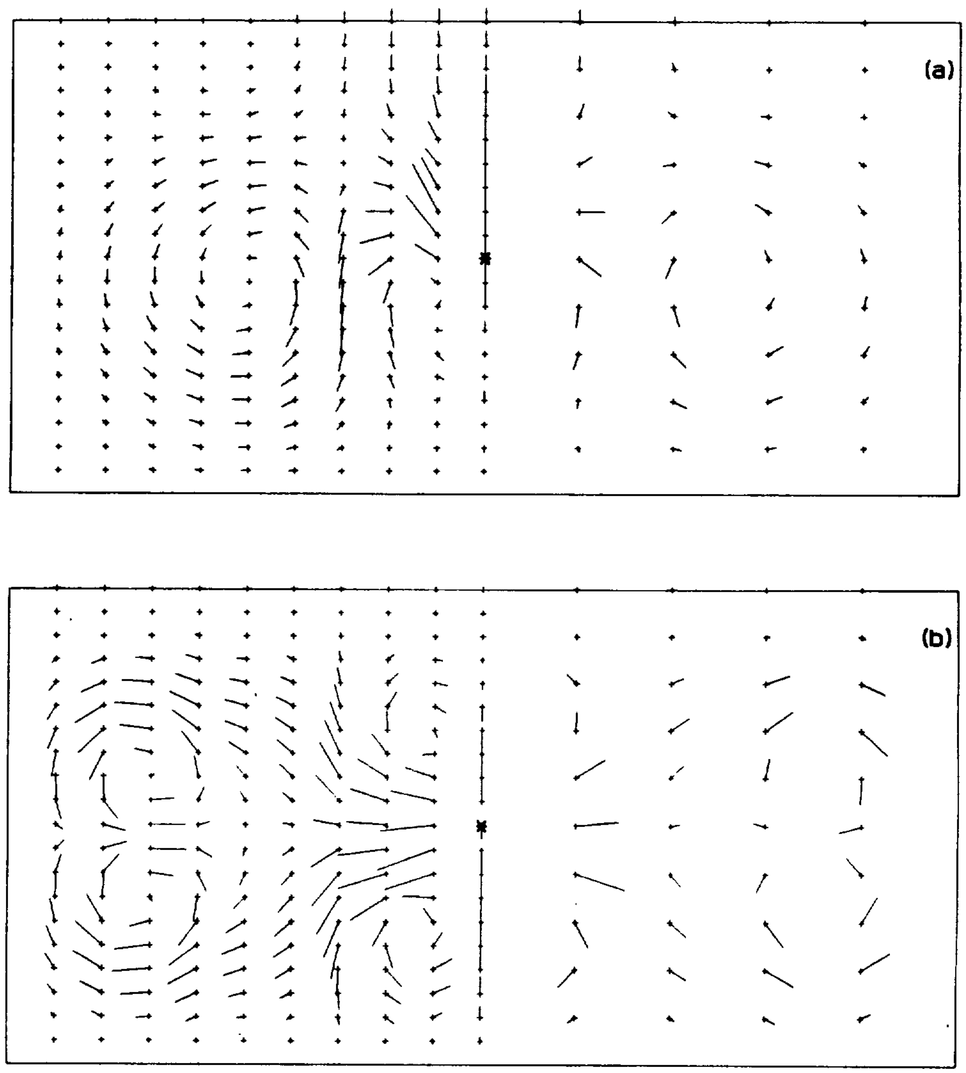



Figure 15. Structural power flow vectors for 333 Hz (a) and 841 Hz (b) modes. Left: high spatial resolution; Right: low spatial resolution. All vectors directly computed.

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16. Abstract


An experimental technique is used to measure structural intensity through an aircraft fuselage with an excitation load applied near one of the wing attachment locations. The fuselage is a relatively large structure, requiring a large number of measurement locations to analyze the whole of the structure. For the measurement of structural intensity, multiple point measurements are necessary at every location of interest. A trade off is therefore required between the number of measurement transducers, the mounting of these transducers, and the accuracy of the measurements. Using four transducers mounted on a bakelite platform, structural intensity vectors are measured at locations distributed throughout the fuselage. To minimize the errors associated with using the four transducer technique, the measurement locations are selected to be away from bulkheads and stiffeners. Furthermore, to eliminate phase errors between the four transducer measurements, two sets of data are collected for each position, with the orientation of the platform with the four transducers rotated by 180 degrees and an average taken between the two sets of data. The results of these measurements together with a discussion of the suitability of the approach for measuring structural intensity on a real structure are presented in this report.


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