Proceedings of the Institute of Acoustics

AN OVERVIEW

David J. W. Hardie

Admiralty Research Establishment, Portland, Dorset DT5 2JS.

INTRODUCTION

Today we have attempted to give an outline of the finite element (F.E.) method, with particular emphasis on applications in the underwater transducer design field. The F.E. method has many attractive features. The method is general enough to cope with a wide variety of situtations. It has a firm mathematical foundation and F.E. techniques are well established [1]. The formulation lends itself readily to standard numerical methods. Producing computer codes based upon F.E. principles is straightforward, if involved and simple effective programs are not difficult to write [2].

Perhaps one of the F.E. method's biggest attractions lies in the ability for an engineer to obtain expertise in the form of advice or software. Commercial codes representing many man-years of effort are widely available and can run on a variety of computer hardware. The degree of complexity is largely problem dependent. A client requiring reletively simple analyses, such as predicting transducer in-air resonance frequencies, may opt for a small P.C. version of an F.E. code. Another engineer may need the services of a supercomputer to tackle a complicated non-linear shock response.

We begin this overview by discussing some of the topics presented during this tutorial. Linear transducer design problems, including aspects of piezoelectric coupling and fluid loading are briefly mentioned. A method for estimating transducer efficiencies is outlined. A few possible further applications of F.E. techniques to other interesting problems in transducer design are given, including a discussion on magnetostrictve devices. A brief summary ends this paper.

APPLICATIONS

Linear analyses

The F.E. method to date has been applied succesfully to a number of problems specific to transducer design. These have been mainly concerned with the statics and dynamics of linear structures. Interesting problems such as determining transducer Head-Flap frequencies are easily dealt with. We have seen today F.E. analyses

Copyright (C) Controller HMSO London 1988

of simple ring transducers and the more common piston-stack devices [3]. In-air resonance frequencies can be predicted to an acceptable degree of accord using relatively coarse meshes. However improving the accuracy of the procedure requires more detailed analysis, paying particular attention to joints in the ceramic stack [3].

An extensive account of F.E. methods applied to a flextensional design including fluid loading effects has also been presented [4]. Reduction in stack pre-stress that occurs while the flextensional transducer is lowered to operational depths is well described. Shear stresses in the G.R.P. shell can be accurately predicted, warning of any likelihood of delamination. The calculation of in-water resonance frequencies agree well with measured values.

Piezoelectricity

The relatively recent formulation and inclusion of piezoelectric finite elements is as a result of demand by transducer designers [5].These elements have specific application to the analysis of the active ceramic material found in most transducer devices today. The results obtained so far are encouraging. Using these elements, forced harmonic response calculations on F.E. transducer models can be performed [6-7]. Admittance loop analysis of transducer models is possible and more elaborate methods of assessment can be performed. Predicting in-air resonance frequencies using piezoelectric elements, although accurate, is no better than using conventional elastic elements with effective moduli to describe the ceramic material. This is always the case when the electric degrees of freedom are clamped.

Reliable material data is always necessary to get accurate results from the F.E. method. This is particularly so when using piezoelectric elements. Most common ceramic piezoelectrics are actually ferroelectrics requiring an initial biasing electric field to be fixed into the material. The piezoelectric properties of the ceramic are sensitive to the degree of initial poling applied. Depending upon the age of the ceramic, it may be appropriate to use degraded values [6]. Improvement in piezoelectric ceramic manufacturing techniques should remove this requirement.

Fluid loading

The effect of fluid loading can be included into an F.E. transducer model. The doubly asymptotic approximation (D.A.A.) is a hybrid F.E. and boundary element (B.E.) formulation which attempts to include the effect of a linear acoustic medium external to a structure [5]. The D.A.A. predicts the natural frequencies of submerged structures well [4-5]. Source levels, receptances etc. are likely to be in only qualitative agreement with experiment, however. A complimentary procedure to the D.A.A. utilising the exact Helmholtz integral equation has been formulated [5]. This is again a hybrid F.E. and B.E. scheme and is therefore computationally expensive, giving rise to dense complex matrices [5]. The method is useful for steady state analysis at a single frequency giving absolute vibration levels. Predicting operational bandwidths is possible, requiring a number of calculations over a range of frequencies.

Surrounding the structure with fluid acoustic elements is another method of incorporating fluid loading effects [7]. Account of the infinite extent of the fluid region must be made. Correct radiating boundary conditions have to be imposed. So-called "infinite" finite elements placed around the fluid F.E. mesh have been employed. Success has been achieved using multipole expansions [7-8]. Here a distribution of damper elements surrounds the fluid mesh. The distribution is weighted to damp out radiating monopole, dipole and higher order waves. All these purely F.E. methods require relatively large fluid meshes, several wavelengths in extent.

<u>Efficiencies</u>
The efficiency of a transducer is an important factor in its design. The more efficient the device, the more acoustic power is produced for a given input voltage. Predicting efficiencies by F.E. methods requires some estimate of radiation damping levels. Fluid loading must be taken into account, either in a semiempirical fashion or more consistently as described above. Also the mechanical and electrical losses in the transducer contribute significantly to the overall efficiency. These loss mechanisms are complicated in nature and are not easily modelled by the F.E. method. Some provision for these losses can be provided by including damping matrices into the F.E. equations. However, experimental data are still needed to estimate the loss factors in the transducer materials.

Incorporating the loss factors, including fluid loading effects and using piezoelectric elements in a forced harmonic response calculation, should give reliable estimates of transducer efficiencies. This is quite an involved task, but the results obtained should be at least as good as those derived from semiempirical methods.

FURTHER APPLICATIONS

Optimisation

A number of commercial F.E. packages contain some capability to optimise designs. This amounts to producing a series of F.E. analyses from which the optimum design is chosen. The engineer can carry this out manually or define certain design criteria with associated bounds and sets up the F.E. input data parametrically. A control program runs the F.E. code supplying new values for the parameters to be used in each trial design. The optimisation process is described in terms of design variables, which are the input parameters subject to change and response variables which are chosen to assess the design. Shell thickness, elastic modulus and shape are all examples of possible design variables. Operating frequency, stress distribution , overall cost and weight are possible responses. An evaluation function is constructed which characterises a design in terms of the response variables.

The whole procedure attempts to maximise the multi-dimensional evaluation function having formulated an initial design. Obviously the closer the initial design to an agreed optimum the better. These facilities enable the transducer engineer to automate his design procedures. An F.E. package with this capability could help in novel transducer designs. For example, ensuring that a useful set of modes have similar frequencies in a broadband device. Head-Flap frequency problems can be easily avoided. Design of flextensional transducers, where experience is not as extensive as in more conventional devices, could also benefit from optimisation programs.

Shock

Naval sonars require a high degree of ruggedness to survive during operational conditions. The sonar hardware must be able to withstand any expected shock loading. The engineer may require to quantify the effects of far-off explosions on transducer mountings or predict failure criteria on ceramic stacks. The F.E. method can be used to model shock loading on sonar structures. This is generally a non-linear acoustic transient problem involving fluid loading. If the fluid can be treated linearly, the hybrid F.E. and B.E. schemes like the D.A.A. can give, at least qualitative, results.

Problems including large structural displacements and cavitation of the fluid are more complicated. They can be tackled, at least in part, using finite difference (F.D.) methods or by hybrid F.E. and F.D. formulations [9]. Access to a supercomputer facility would be beneficial here.

Magnetostrictive transducers

The desire to develop low frequency active transducers with increasingly higher source levels has revived interest in magnetostrictive devices. Recently discovered Rare Earth alloys , such as Terfenol (Terbium, Iron, Dysprosium, alloy), show promise as active materials, with large magnetic coupling coefficients. The design of practical magnetostrictive transducers suffers from the difficulty in restricting the magnetic field to the region of the active material only. Terfenol has a low relative permeability close to that of air. An A.R.E. design performed poorly owing to significant leakage of magnetic flux [10].

The F.E. method has been sucessfully used in the field of heavy-current electrical engineering. Analyses of magnetic fields, mutual inductance and flux lines are performed routinely by suitable codes. Both scalar and vector potential formulations of Maxwell's equations have been developed. Non-linear saturation behaviour of certain permeable materials can be described. Obviously, these methods can be employed to aid design of magnetostrictive transducers. Accurate predictions of the magnetic circuit within the transducer will be important, especially if the new low permeable alloys with large couplings are used. To the author's knowledge, no magnetostrictive finite elements have been developed.

Depth compensation

Transducers are affected by hydrostatic loading. Stress stiffening changes the resonance frequency as the transducer changes depth. This results in a loss of efficiency, as the driving frequency is unchanged. Flextensional transducers are particularly sensitive to outside pressures. The shell may deform to such an extent that all mechanical coupling from the ceramic stack is lost. The ceramic may be damaged in this extreme case.

To counteract hydrostatic loading requires some mechanism for depth compensation. This usually means that a corresponding internal pressure must be varied to balance the outside water pressure as the transducer changes depth. The F.E. method can analyse the efficacy of possible depth compensation schemes. This amounts to a complicated non-linear problem. Not only does stress stiffening of the ceramic stack occur but material non-linearities may become significant. Surfaces may come into contact requiring gap finite elements to be included and large structural displacements may ensue.

SUMMARY

This tutorial has outlined the F.E. method [1], discussed aspects of programming the algorithm [2] and given some transducer design applications [3-4]. We see that the F.E. method has great potential as a design tool. More involved problems arising from novel designs and applications may only be solved using F.E. techniques.

The transducer design engineer of tomorrow may need to be a dedicated F.E. expert. We hope not, although complicated problems may require specialist knowledge. Certainly, experience of F.E. and other numerical techniques is likely to become increasingly important in the underwater transducer field.

However we warn the beginner: F.E. analysis is more involved than it may first appear; experience does count. An F.E. mesh may look attractive in a glossy report but the tabulated results need interpretation and careful scrutiny: something that computers cannot do, yet.

In the final analysis, the engineer's physical intuition and his design experience are all that he can rely upon.

REFERENCES

[1]. B. V. Smith, "Finite element principles", in Finite Elements Applied to Sonar Transducers - Institute of Acoustics Tutorial, 1988.

[2]. J. R. Dunn, "Structure of a simple program", in Finite Elements Applied to Sonar Transducers - Institute of Acoustics Tutorial, 1988.

[3]. A. B. Gallaher, "First experiences using a commercial FE package - a case history", in Finite Elements Applied to Sonar Transducers - Institute of Acoustics Tutorial, 1988.

[4]. R. J. Brind, "Application of FE to a flextensional transducer", in Finite Elements Applied to Sonar Transducers -

Institute of Acoustics Tutorial, 1988.

[5]. P. C. Macey, "Fluid loading (radiation) & piezoelectric elements", in Finite Elements Applied to Sonar Transducers - Institute of Acoustics Tutorial, 1988.

[6]. H. Allik and K. M. Webman, "Vibrational response of sonar transducers using piezoelectric finite elements", J. Acoust. Soc. Am. 56, 1974

[7]. J. T. Hunt, M. R. Knittel, D. Barach, "Finite element approach to acoustic radiation from elastic structures", J. Acoust. Soc. Am. 55, 1974.

[8]. R. Bossut and J. N. Decarpigny, "Finite element modelling of radiating structures using dipolar damping elements", submitted to J. Acoust. Soc. Am.

[9]. G. L. Goudreau and J. O. Hallquist, "Recent developments in large scale finite element Lagrangian hydrocode technology", J. Comp. Meths. Appl. Mechs. Eng. 30, 1982.

[10]. J. R. Oswin and R. J. Edenborough, "Rare-earth magnetostriction and low frequency sonar transducers", presented at I.o.P./I.E.E./I.E.E.E. seminar "Magnetic sensors and amorphous materials", 1988.