COMPUTATIONAL MODELLING OF CORIOLIS MASS FLOWMETERS

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A B S T R A C T

Initial results are presented from a theoretical study of Coriolis mass flowmeters complementing experimental testing at NEL. The theoretical approach employs finite-element structural analysis (FEA) incorporating a simplified Coriolis force model to derive natural vibration frequencies, calibration characteristics and detailed stress distributions for commercial meters. Progress on developing a computational fluid dynamics (CFD) Coriolis force model is also discussed.

1 INTRODUCTION

The present work is linked to a wide-ranging collaborative mass flowmeter research programme in which the National Engineering Laboratory (NEL) has a prominent role. The aim is to develop a theoretical method to complement experimental testing of Coriolis meters with the overall aim of assessing their generic performance. The computer model will be of use in obviating the need for repetitive testing, confirming experimental findings or investigating influences outwith the scope of experiment. Initially, however, the model itself must be tested against experimental data for typical meters. This is the concern of the present paper.

In keeping with the spirit of a workshop forum, the paper concentrates on the results and their practical significance, rather than the minutiae of the mathematical model. Those interested will find detailed descriptions of the model in subsequent publications by the author.

2 OPERATING PRINCIPLE

A Coriolis mass flowmeter is essentially a vibrating pipe conveying the flow of fluid, Fig. 1. Both ends of the pipe are fixed and the vibration is forced, generally at the mid point, by means of an external driver. Fluid entering the pipe acquires translational motion increasing to a maximum at the drive point. An increase in the transverse velocity of the fluid implies an acceleration and hence an applied force. This is imparted by the inner wall of the moving tube which as a result loses energy, lagging behind the motion of the driver. On the other side the opposite occurs with the outlet limb moving in advance of the driven motion as energy is released when the fluid vibration is dampened to zero again. The end effect is an asymmetric twisting motion superimposed on the driven or bending motion, where the degree of twist is a measure of the fluid mass flowrate.

The forces on the fluid and the reactionary twisting of the pipe are due to the Coriolis effect, named after the French scientist, Gustave-Gaspard Coriolis (1792-1843). He first described how a body moving in a rotating frame of reference experiences an inertial force at right angles to its direction of motion [1]. The most familiar example of the Coriolis effect are the cyclonic weather patterns caused by the rotation of the earth.

3 MODELLING TECHNIQUES

The problem of modelling Coriolis mass flowmeters is a challenging one involving coupling between structural and fluid dynamics. Previous researchers [eg 2, 3, 4] have tended to favour analytical methods which, while mathematically rigorous, lack realism in terms of their treatment of fluid effects or structural features such as bracing members or fixing constraints. In addition, results from these methods apply only along the centre line of the structural member, or "beam", and so stress solutions, for example, become somewhat meaningless for a pipe.

At least one "beam theorist" concedes the need to employ the alternative technique of finite-element analysis (FEA) in at least a secondary modelling role [3]. Although less eager to publish, meter manufacturers are also known to be using FEA to model their meters in-house [eg 5].

FEA forms the basis of the present work, providing vibration frequencies, displacements and stresses for realistic meter configurations. The Coriolis effect is introduced through an external load vector generated either directly by means of a simplified mathematical model, or using computational fluid dynamics (CFD) techniques with the potential to predict local fluid effects. The present results are mainly obtained using the former simplified model, though initial qualitative CFD results are also presented. To the author's knowledge, no one using FEA to model Coriolis meters has gone beyond free-vibration analysis to include Coriolis effects, and in particular the use of CFD in this context appears to be a first.

3.1 Structural Analysis

The finite-element method is an established numerical procedure for static and dynamic analysis of structures [6, 7]. The structure is modelled as an assemblage of discrete elements small enough for reliable approximations to be made concerning the distribution of variables within each element. The governing equations (force-displacement, stress-strain, etc) are solved at the element connecting points, or nodes, entailing solution of a large number of simultaneous equations, roughly as many as there are nodes. FEA therefore usually implies the use of a high-speed computer running specialised software.

The general-purpose finite-element software package, ANSYS, is used in the present work. ANSYS can predict natural frequencies, displacements, stresses and phase relationships under harmonic loading conditions. (Coriolis meters are driven harmonically, typically at their fundamental frequency to save power). Quadrilateral shell elements are used to model the meter tubes and three-dimensional solid elements are used for the end supports. Concentrated mass elements are used to represent the driver/ pick-up coils and magnets. The Coriolis effect is introduced through a nodal load vector generated by a simplified mathematical model outwith ANSYS. The model computes the Coriolis force distribution from a given 'bulk' mass flowrate independent of fluid properties or local variations in velocity.

3.2 Fluid Analysis

While the simplified Coriolis force model appears to give acceptable results (see below), a computational fluid dynamics model is also being developed to investigate possible secondary influences such as density or viscosity effects. Another commercial software package is being utilised for this purpose, the established CFD code PHOENICS. This is used as a vehicle for solving the Navier-Stokes fluid flow equations where these have been specially modified to account for Coriolis effects.

The CFD analysis yields three-dimensional, time-dependent, Coriolis pressure distributions for the fluid oscillating within the pipe. These will be transferred to the structural model, in effect providing the boundary conditions for the forced-response analysis in ANSYS. The PHOENICS Coriolis model itself depends on the ANSYS solution, calling for an iterative procedure between the two.

4 RESULTS

Although developed for the purpose of a purely generic study, the theoretical model needs to be 'bench-tested' against performance data for individual meters. Discussed below are selected results for a commercial example of the straight-tube type of meter.

The finite-element model is shown in Fig. 2. ANSYS employs symmetry and hence only half of the structure is shown. (Twin tubes are a common feature of Coriolis meters to compensate for ambient vibrations.) As shown, the tubes are set into end supports/manifolds, whose outer flanges are set fixed.

Before commencing the analysis, the suitability of the finite-element mesh was assessed in a parametric study of the effect of mesh density on the predicted natural frequencies. As the mesh is continually refined, the predicted frequency is expected to reach an asymptote as appoximations inherent in the FE method introduce progressively less error. Figure 3 is an example showing the effect of increasing the number of circumferential divisions on tube fundamental frequency. Refining the circumferential spacing reduces the percentage error with reference to the 'infinite' asymptotic value. Another plot shows axial divisions as the independent variable. From these results the required mesh density could be found which gave reasonable accuracy, eg less than 1 per cent error, without over-refinement.

ANSYS was then used to calculate the natural frequencies and mode shapes of the optimised model assuming free, undamped vibrations. The fundamental frequency (ie the driven frequency) is that of most interest and was compared with the experimental value for the meter in air. Extremely close agreement was obtained for this particular meter, eg a predicted frequency of 1128 Hz compared with 1126 Hz experimental. However, it should be reported that, in contrast, roughly 5 per cent discrepancy was obtained for another, larger, version of the same type of meter (the standard deviation among real meters is ± 2 per cent [8]). A likely explanation is that, although the tube mesh density may have been optimised, the solid end supports remain relatively crude representations. The effect of refining the modelled end supports is to be investigated in the near future.

The Coriolis force model was then used to generate nodal load vectors over the meter's recommended flow range and a series of harmonic analyses was run resulting in the calibration characteristic of Fig. 4. It can be seen that the predicted sensitivity is close to the experimental value, in fact 1362 ns/kg/s compared with 1377 ns/kg/s respectively. The phase lag of the ordinate is between points corresponding to the pick-up sensor locations.

Coincidentally, the technique may also be used to determine optimum sensor location as shown in Fig. 5. Although referring to another meter, this shows the effect of increasing pick-up separation on flowrate sensitivity. It can be seen that for a straight-tube meter the sensitivity increases with pick-up separation, being greatest with the pick-ups at the ends of the tube. However, this is where the displacement goes to zero, obviously, and hence in practice a compromise separation is typically two-thirds of the tube length. The prospect of maximising sensitivity in this way has led to interest in the use of fast-response strain gauges for measuring the deflection close to the tube roots.

Stress intensity contours are shown in Fig. 6. The regions of highest stress are clearly seen to be around the drive node and near to each end.

Coriolis meters are inevitably susceptible to fatigue failure due to repeated stress cycling. The maximum allowable stress is limited by the fatigue or endurance limit of the material concerned, in this case titanium. Comparison with the present result is shown in Fig. 7. This indicates that the predicted maximum stress can be considered 'safe', ie irrespective of the number of stress cycles, the fatigue limit is never reached. It should be remembered, however, that the fatigue limit can decrease due to corrosion or with increasing temperature [9].

Finally, Fig. 8 is a composite plot of CFD predictions for the fluid pressure field as the oscillation goes through one half cycle from (mid line to end of travel and back again). The CFD grid is three-dimensional (cylindrical polar) and the grid dimensions and the solution parameters are representative of an actual meter. The contours are plotted in the plane of the vibration as though the tube had been cut in half. Perhaps contrary to first thought, it can be seen that the Coriolis pressure field and hence the Coriolis force is at a maximum as the pipe passes through the mid line, fading to zero at the end of the travel. This should be expected, however, as, after all, the Coriolis force is derived from the motion of the pipe. Whenever the pipe is moving and provided the fluid is flowing, an asymmetric pressure field results which presses on the inner wall causing the pipe to twist about the mid point in the Coriolis mode. The pressure contours shown in Fig. 8 could be said to have real significance therefore, being directly responsible for the asymmetric twisting motion by which the Coriolis meter works.

5 CONCLUDING REMARKS

Although to be developed further, the present model is shown to be a promising tool for analysing Coriolis mass flowmeters and helping to assess their generic limitations. Meters can be modelled more realistically, yielding critical information on endurance limits for safe operation for example.

While use of a simple algebraic Coriolis force model is seen to give acceptable results, progress has been made on developing a novel computational fluid dynamics (CFD) technique with the potential to predict local fluid effects. Whereas most models assume a given 'bulk' mass flowrate, the CFD approach uses local fluid velocities and depends implicitly on fluid properties such as density or viscosity. The CFD model could conceivably provide a means of investigating known problem areas such as two-phase flow or gas compressibility effects.

Future work will include further testing of the basic model against different meter designs (eg u-tube type) and further integration of the CFD. Parametric studies of the effect of fluid properties are planned also.

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REFERENCES

[1] CORIOLIS, G-G. On the equations of relative motion of systems of bodies, Paris, 1835.

[2] HEMP, J. and SULTAN, G. Modelling of the Coriolis mass flowmeter. J. Sound and Vibration, 1989, p. 132.

[3] HEMP, J. and SULTAN, G. On the theory and performance of Coriolis mass flowmeters. IBC Int. Conf. on Mass Flow Measurement, London, 1989.

[4] KEITA, N. M. The zero drift effects in Coriolis mass flowmeters. IBC Int. Conf. on Mass Flow Measurement, London, 1989.

[5] McKENZIE, G. L. Mass flow measurement - Short course notes. Cranfield Institute of Technology, 1988.

[6] NAFEMS. A finite element primer. National Engineering Laboratory, Glasgow, 1986.

[7] DAVIES, A. J. The finite element method. Clarendon Press, Oxford, 1980.

[8] KEITA, N. M. Personal communication, 1990.

[9] BOYER, H. E. Atlas of fatigue curves. American Society for Metals, 1986.

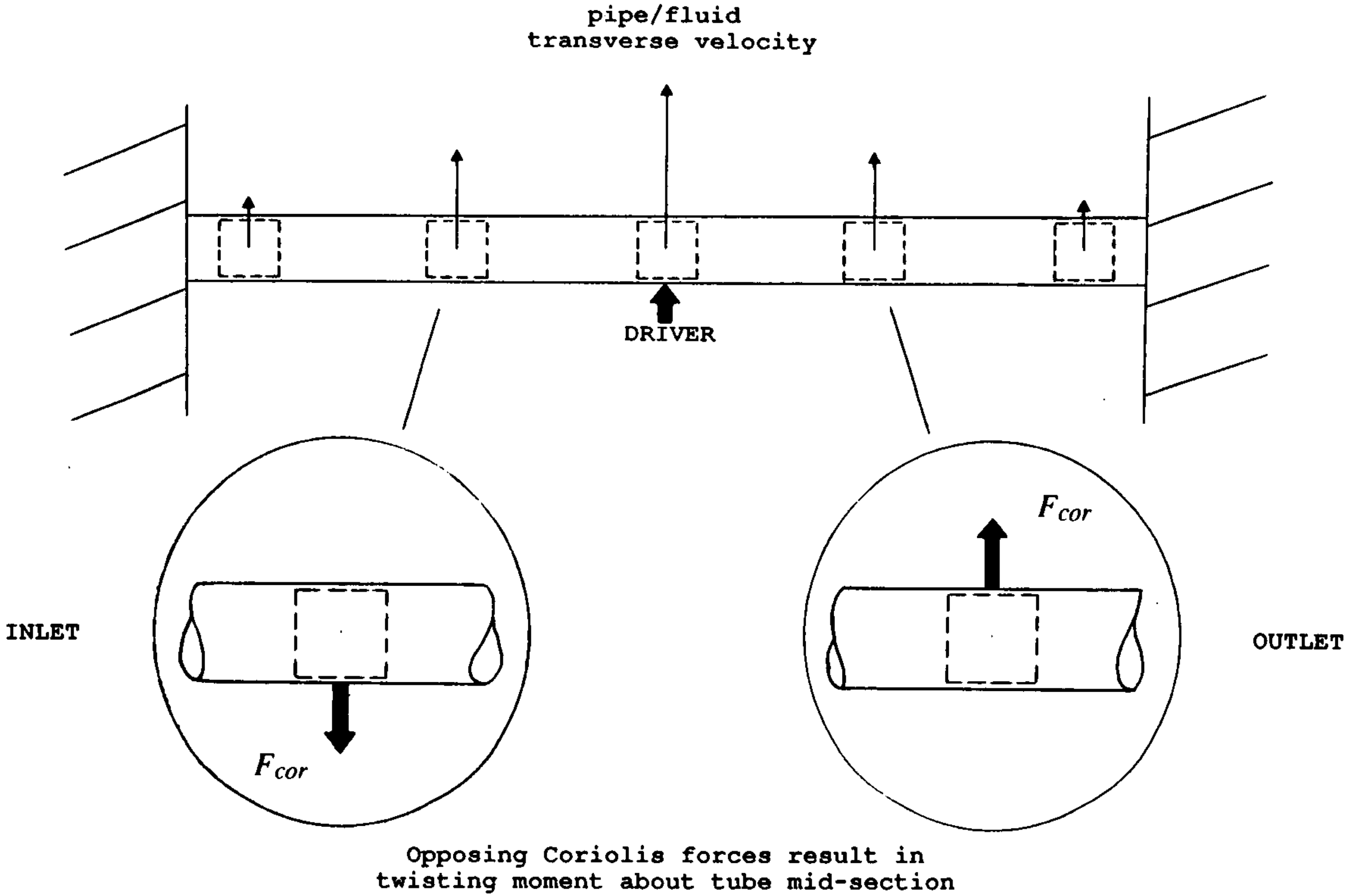

FIG 1 SCHEMATIC OF CORIOLIS MASS FLOWMETER SHOWING PRINCIPLE OF OPERATION

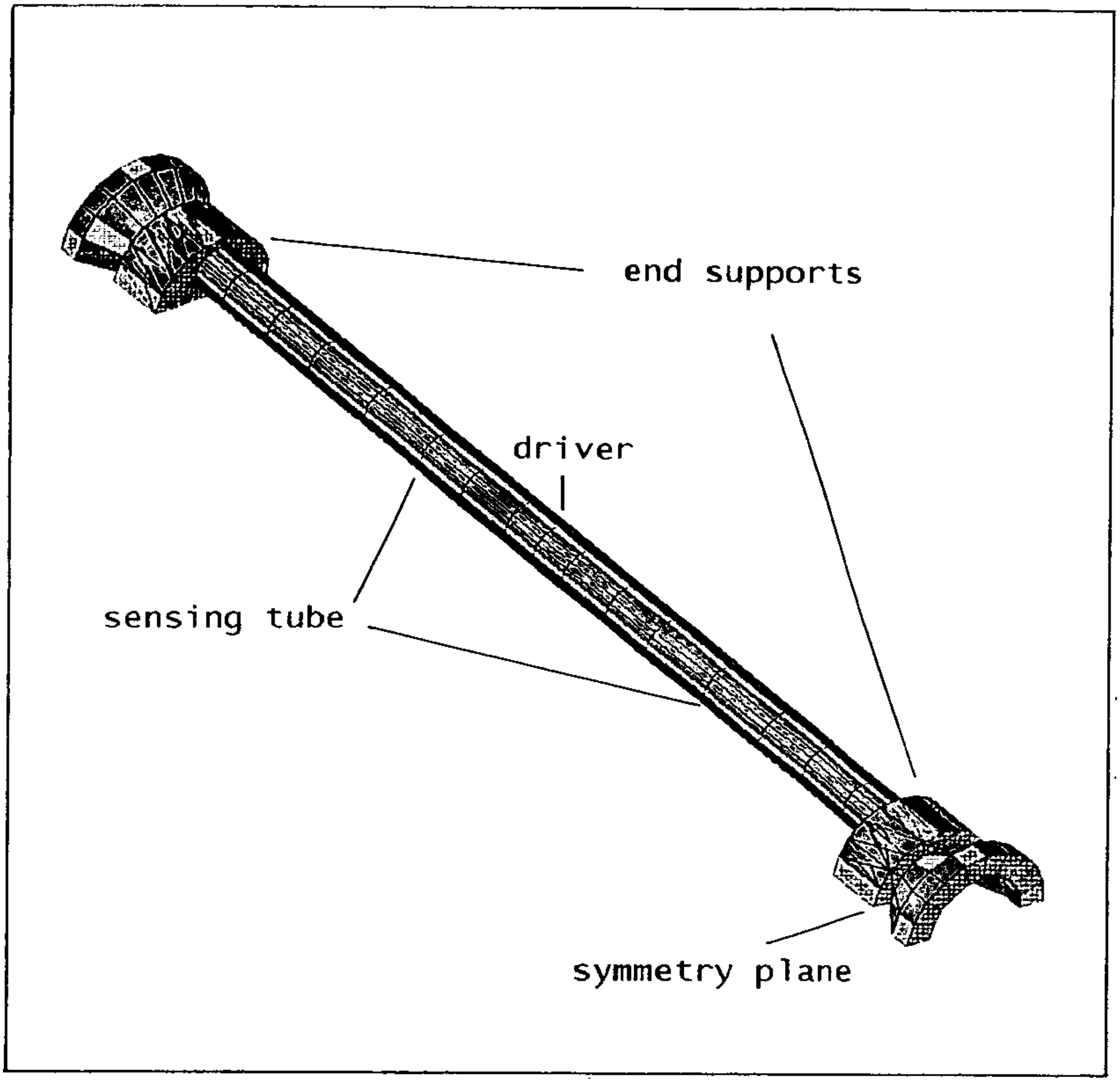

FIG 2 FINITE-ELEMENT MODEL OF STRAIGHT-TUBE METER

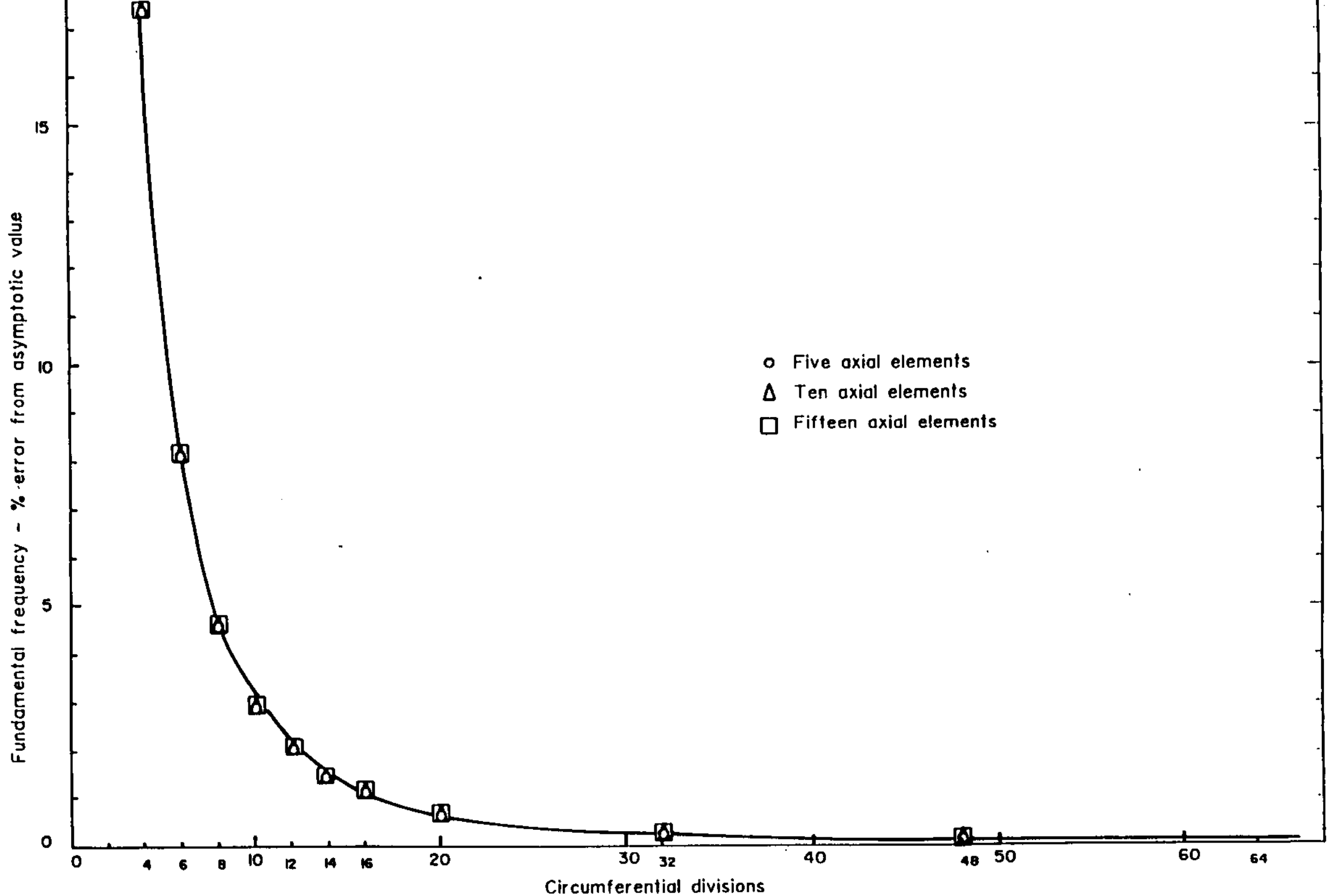

FIG 3 EFFECT OF MESH DENSITY ON PREDICTED FREQUENCY

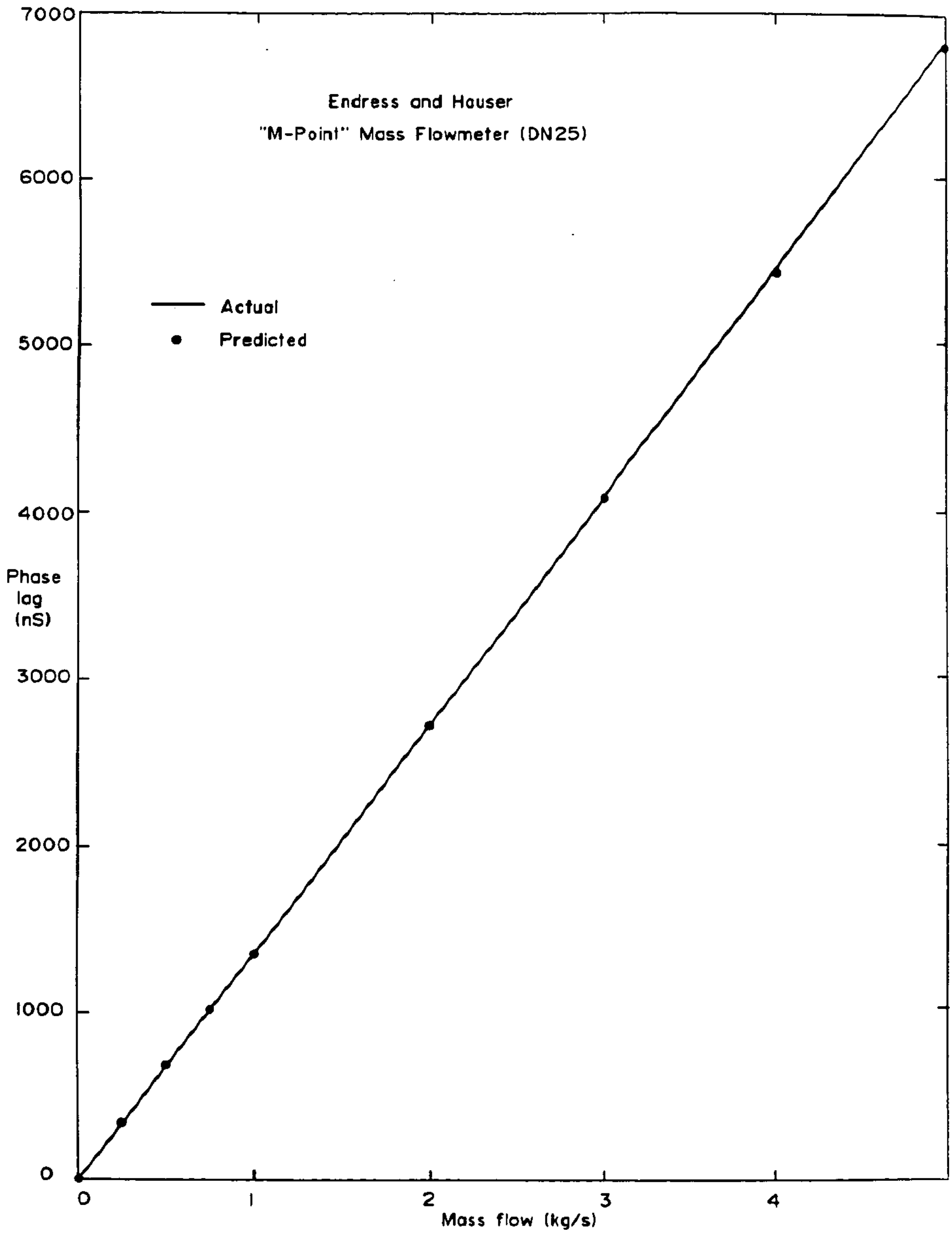

FIG 4 CALIBRATION CHARACTERISTICS

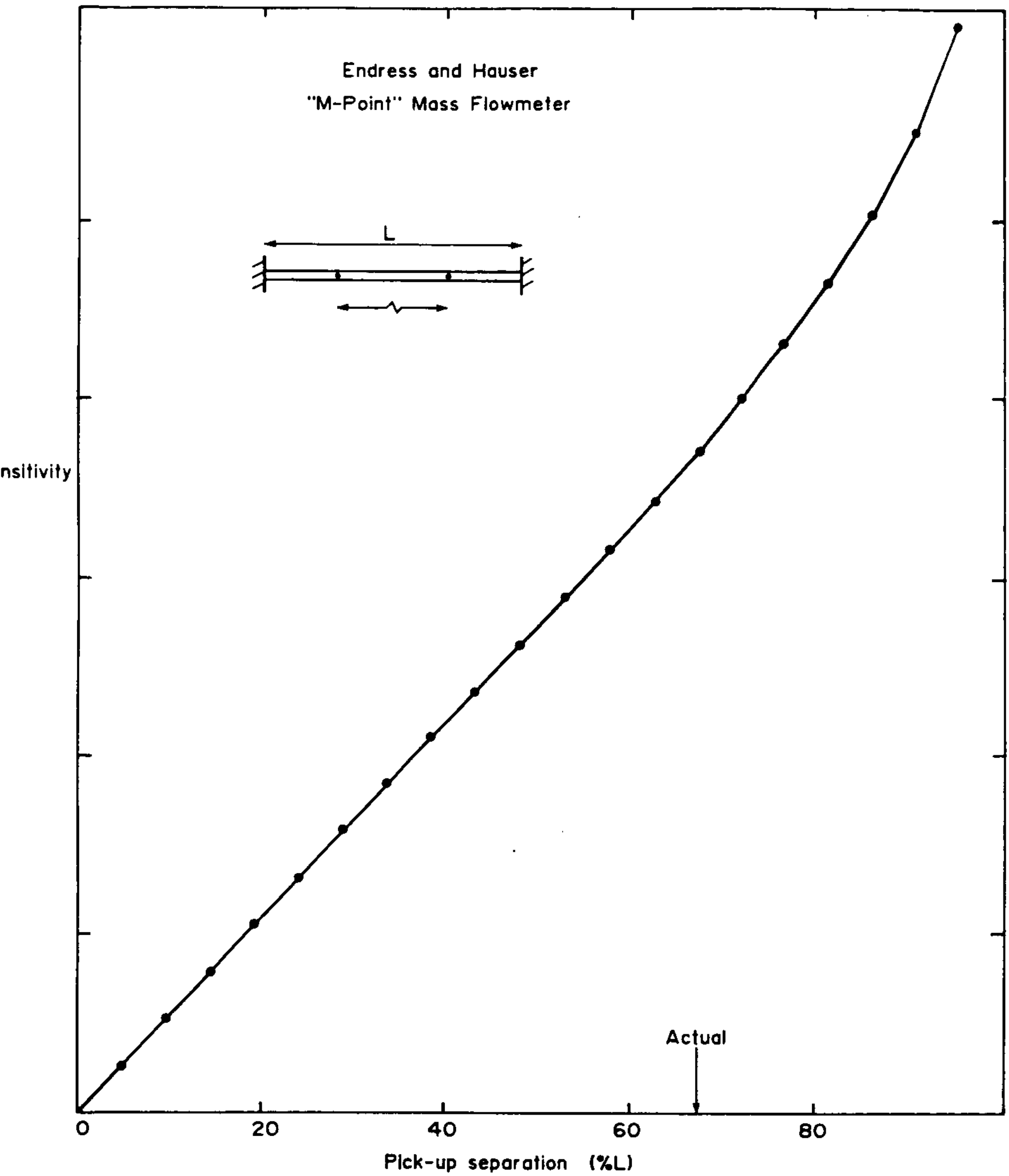

FIG 5 EFFECT OF PICK-UP LOCATION ON METER SENSITIVITY

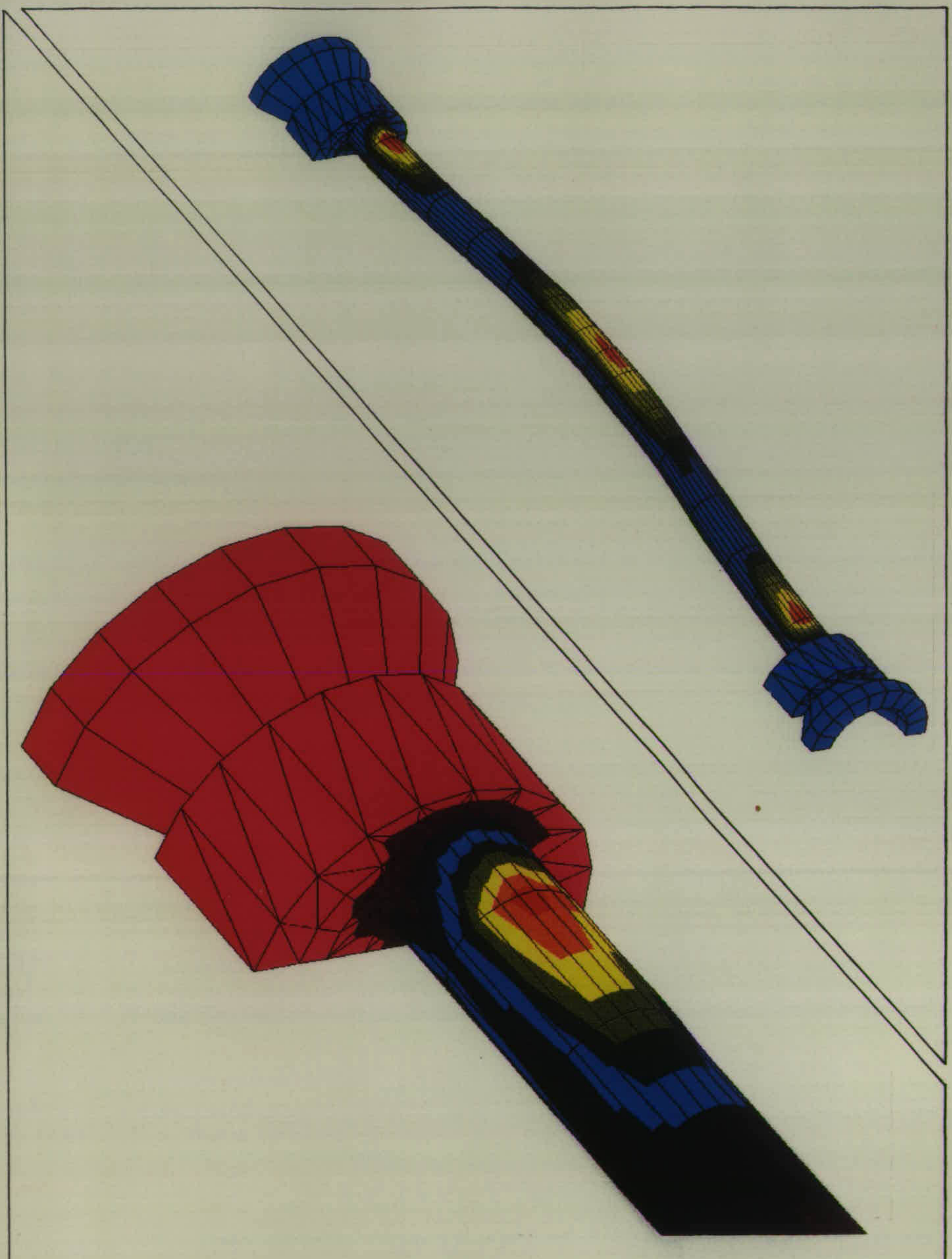

FIG 6 FINITE-ELEMENT STRESS CONTOURS

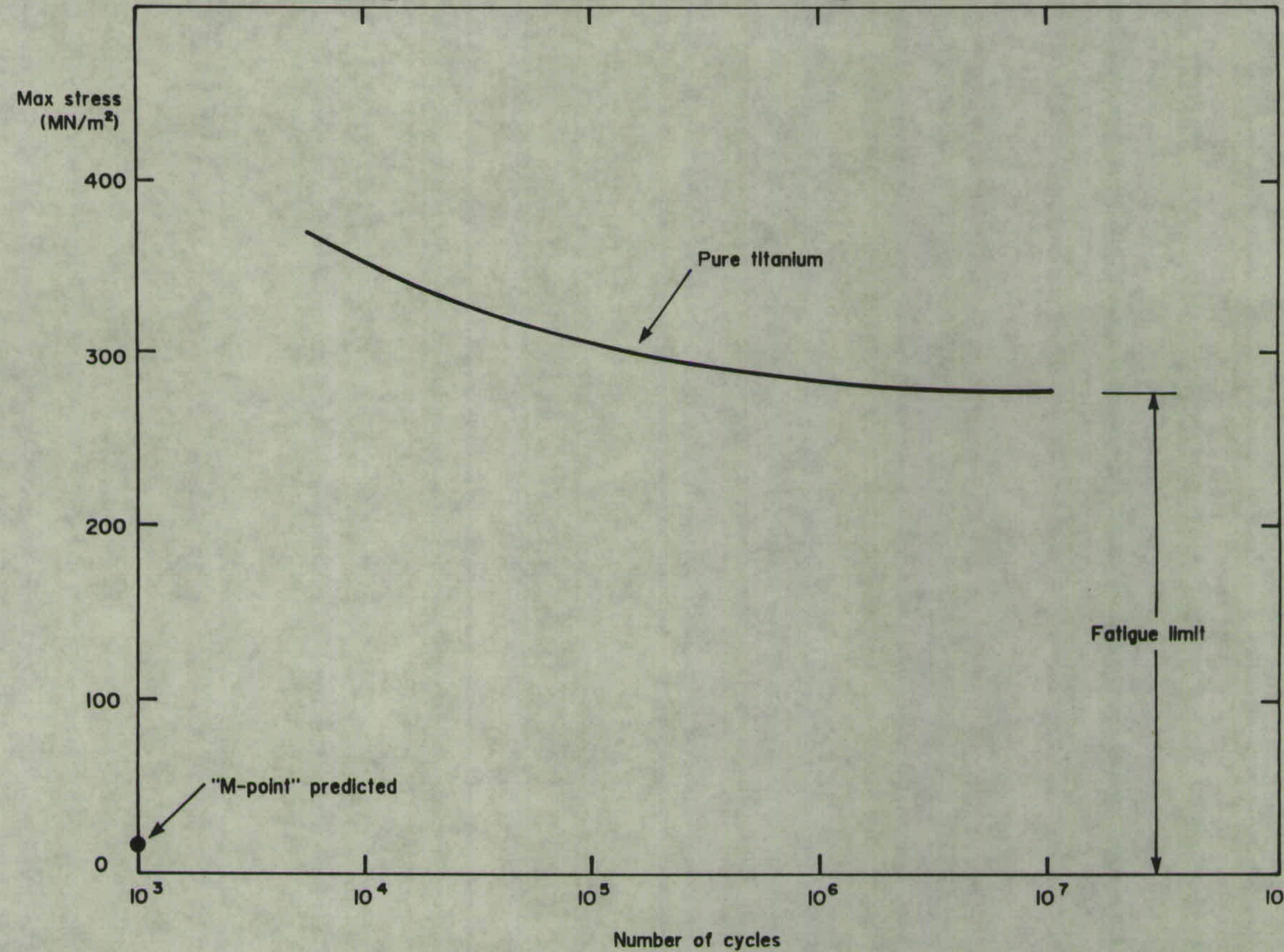

FIG 7 COMPARISON OF PREDICTED MAXIMUM STRESS WITH MATERIAL FATIGUE CURVE

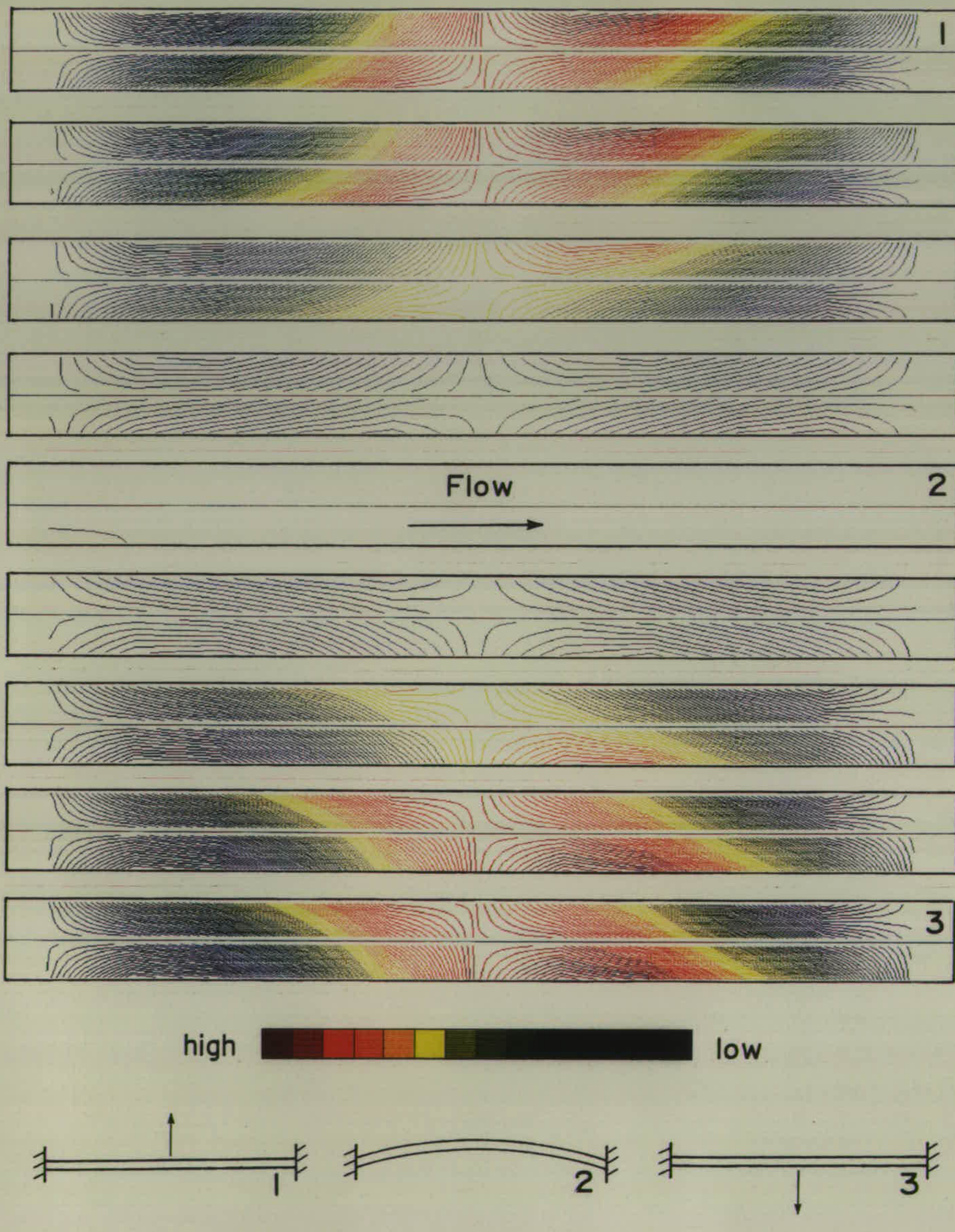

FIG 8 CFD FLUID PRESSURE CONTOURS