Applications of FEM Analysis in Engine Development

1. Introduction

To address environmental issues and at the same time supply products that are attractive and of high quality to the market, Nissan is adopting predictive development based on the latest computer-aided engineering (CAE) technology in engine development.

To achieve efficiency in the development from an early stage of engine development to the making of a highly complete prototype and finally to the mass production stage, a tool for advance evaluation of engine performance, function, and reliability is needed. The use of computer simulation technology has become indispensable for that purpose.

Here, we briefly introduce the incorporation of CAE technology into actual engine design work and the current state of affairs, presenting some specific examples that focus on finite element method (FEM) analysis.

2. The Adoption of CAE

The application of CAE in engine development by Nissan at first mainly involved the use of one-dimensional cycle simulations to predict engine performance and the use of finite element methods in strength and stiffness simulations for engine components. The analysis domains were then expanded step-by-step to include the prediction of driveability and fuel consumption concerning performance systems and vibration analysis, heat conduction and thermal fatigue analysis for engine component systems. Most recently, the development of hardware and software is making it possible to apply large-scale analysis systems such as three-dimensional computational fluid dynamics (CFD) in engine design, and it has become possible to predict the air flow dynamics of the intake manifold and the coolant velocity distribution in the cylinder head with rather good accuracy. Thus, the fluid-structure coupling analysis that is required for the prediction of thermal stress in the various components under operating conditions has also become possible.

The use of FEM analysis up to now is described in the next section.

3. Use of the FEM

3.1 Engine intake noise prediction using the FEM

The lowering of vehicle noise is an important problem with respect to high quality and noise legislation. There is also a strong demand for both increasing engine output performance lowering noise and vibration, which are in a trade-off relationship. There is a particular need for ways to predict and reduce engine intake noise, which is one major contributor to vehicle noise.

Although the four-pole parameter method and one-dimensional cycle simulation have conventionally been used as predictive techniques in the design of intake systems, those methods are not able to determine the geometry other than diameter and length and are limited to the high frequency range in terms of accuracy of prediction. To overcome those limitations, we are developing and applying a method in which a three-dimensional finite element(FE) model of the air space of the actual intake system is constructed, the excitation force for each cylinder is given, and the intake noise from the end of the air duct is computed directly.

(1) Basic approach and process of intake noise analysis

The acoustic analysis is performed by using MSC/NASTRAN as the analysis solver. One feature of this analysis is the input of the acoustic excitation force into the FE model, which is accomplished by using structural-acoustic coupled analysis.

An outline of the computational procedure up to the output of the intake noise values is presented in Fig. 1.

The three-dimensional FE model of the entire air space of the intake system is constructed in parallel with the computation of the one-dimensional cycle simulation. The results of the cycle simulation are used as the sound source of the intake noise, the acoustic excitation force from the cylinder head port is given, and the sound pressure level and sound pressure mode of the air duct are obtained.

(2) An example for intake noise

The results of intake system sound pressure mode computed for a six-cylinder gasoline engine by intake noise analysis are shown in Fig. 2.

These sound pressure mode and sound pressure level values are being used to determine the specifications and positioning of a silencer in a study on sound performance design of the intake system. An example from a study of air duct resonator capacity for reducing the third-order harmonics sound pressure level to the target value is shown in Fig. 3.

This analysis allows the prediction of engine rotation 0.5th-order harmonics sound pressure level and high-frequency range noise level in the 1kHz frequency range, and the early use of this method in the design of air ducts is being decided.

3.2 Cylinder head strength and stiffness analysis

The cylinder head, one of the main engine components, is used under severe conditions of both load and temperature, so it is essential that this component be given sufficient study in the design stage. To that purpose, advance design evaluation is performed through detailed analysis by means of FEM and CFD.

Cylinder heads are clamped by cylinder-head bolts, and are subjected to high temperature and pressure load from the combustion, resulting in high stress around the periphery of the combustion chamber.

An example of evaluating the stress on the cylinder head when combustion pressure is input is presented in Fig. 4. The analysis shows that for the initial shape, the stress exceeds the fatigue limits of the material, and thus that the shape must be changed. An overall stiffness balance in the cylinder head is important. Even if the stress is reduced in one area of concentrated stress, the concentration of stress may be moved to another area. For that reason, an FEM study of stress in the entire cylinder head is necessary. Here, too, a number of shape factors, such as filet radius, wall thickness, and rib shape, were studied to obtain a solution that reduces the overall stress to below the fatigue strength limits of the material. The reduction in stress predicted by the computations was then confirmed by experiment.

The obtained overall temperature distribution and thermal stress of the cylinder head is shown in Fig. 5. The measured combustion chamber temperature and pressure and the bolt tightening force and the predicted heat transfer coefficient between the water jacket walls and the coolant that was obtained from the flow analysis results are given as the boundary conditions. The overall temperature distribution and the associated thermal stress was calculated by using MSC/NASTRAN. The FEM analysis prediction shows high compression stress generated around the exhaust valve sheet.

For reference, the velocity vector results from the flow analysis are presented in Fig. 6. From the LDV results, the correlation coefficient between the results of analysis and experiment was 0.92, indicating that the computation is sufficiently accurate.

In this way, the combination of both FEM and CFD has also recently been adopted, albeit in part, for coupling analysis.

3.3 Application to structural vibration analysis

Structural vibration analysis is another problem that often arises in the development process.

The FE model for a study of the reduction of radiated noise produced by vibration in a fuel injection pump bracket in the process of developing a new four-cylinder diesel engine is shown in Fig. 7. The initial design prototype had a radiated noise peak in the near 1 kHz, which required improvement. That peak has been determined to arise from the excitation force from the gear-driven vacuum pump mounted on the injection pump bracket.

A finite element system model was constructed with MSC/NASTRAN, and a very high correlation with the measured vibration level and the radiated noise was obtained.

When, after investigating the near 1kHz peak level mode, the same evaluation was performed with an analytical model in which the mounting bracket shape and mounting position on the cylinder block were changed, the large peak at 1 kHz that was seen for the initial design did not appear and the radiated noise in that frequency range was greatly reduced. The acceleration levels before and after the improvement are compared in Fig. 8.

4. Conclusion

We have briefly described the current state of the use of FEM analysis in engine development through specific examples.

Because future engine development will be more complex and technology will progress to yet a higher level, the role of CAE will become more important.

At the present stage, on the other hand, many difficult problems remain for predictive techniques, including the non-linear analysis of friction, wear, and noise, which are problems for the structural system . Those problems include the need for the linking of test data and analytical simulations and the step-wise expansion of the areas in which prediction is possible. There are also many issues regarding technology that is already in practical use, such as shortening structure modeling lead time, further increasing the accuracy and reliability of computations, and simplification of analytical tasks. In the near future, however, further progress in hardware and software can be expected, and we believe that the direct computation of complex physical phenomena and large-scale models of complete systems conventionally believed impossible may indeed become possible. The possibility of evaluation of basic performance and function of components and of the system as a whole by computer simulation prior to actual engine promises to greatly reduce the need for prototypes and testing.

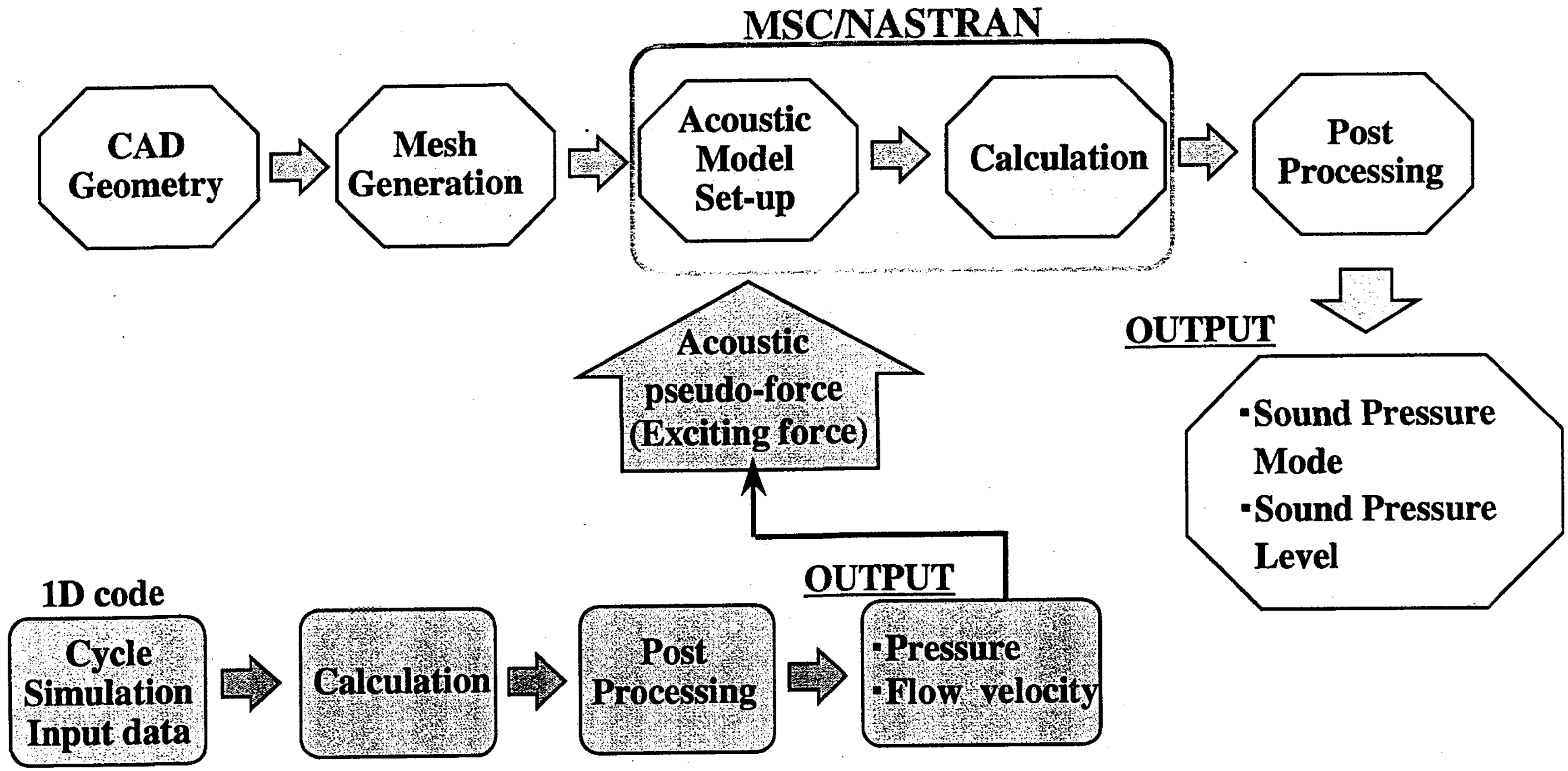

Fig1. Basic Flowchart of the Intake Noise Analysis

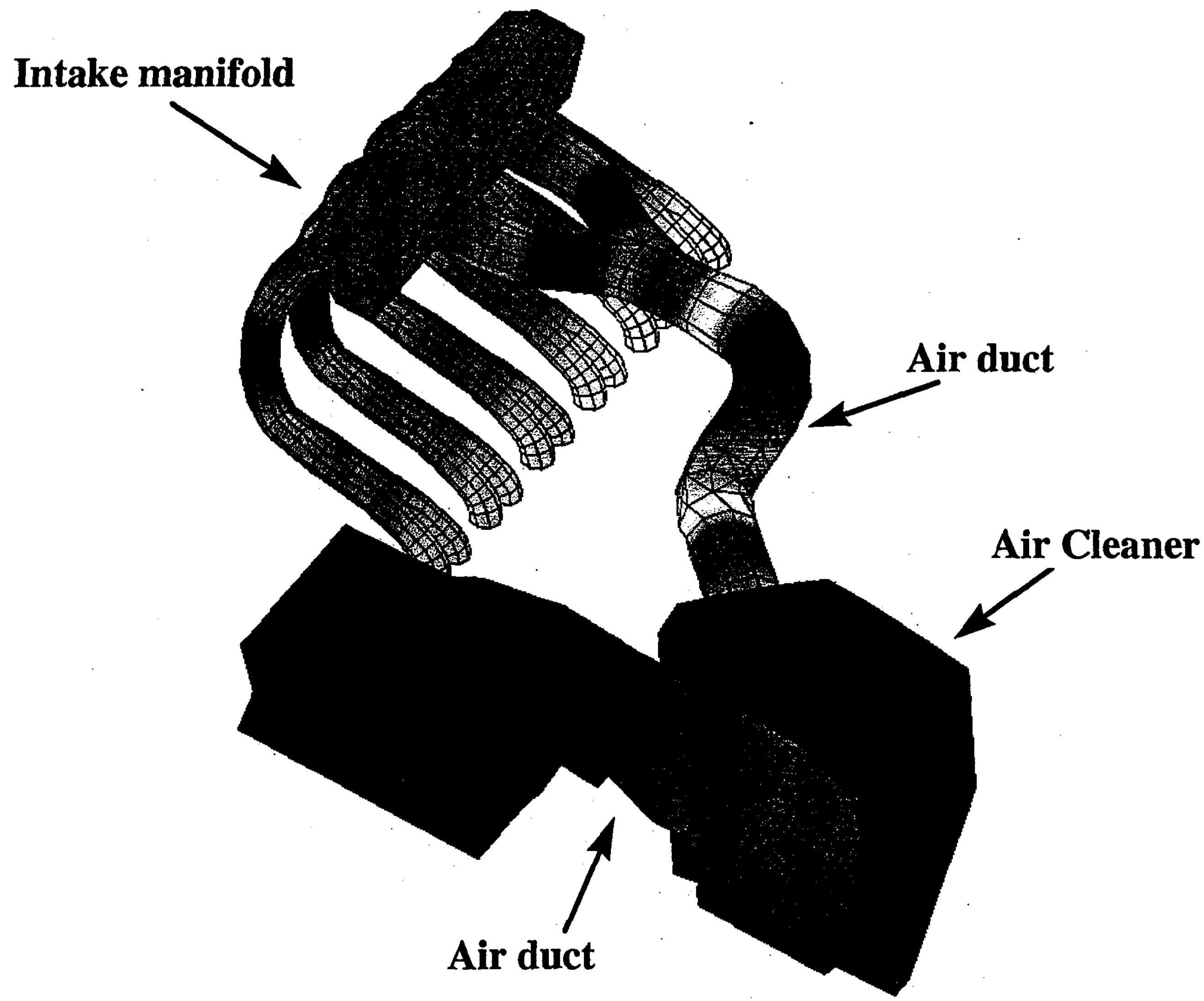

Fig 2. Example of a Sound Pressure Mode

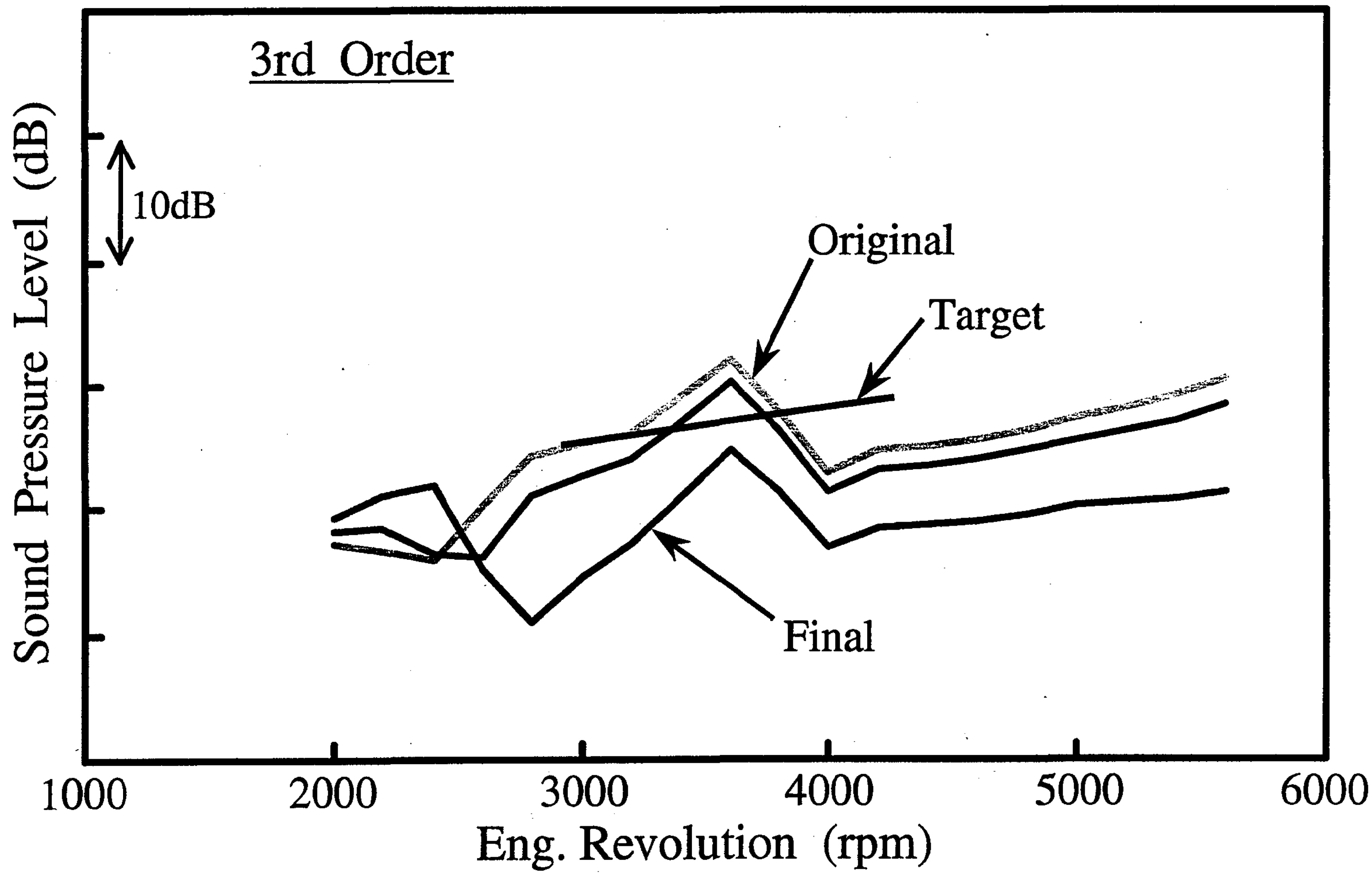

Fig3. The Influence of dust-side resonator capacity : Sound Pressure Level of 3rd Order

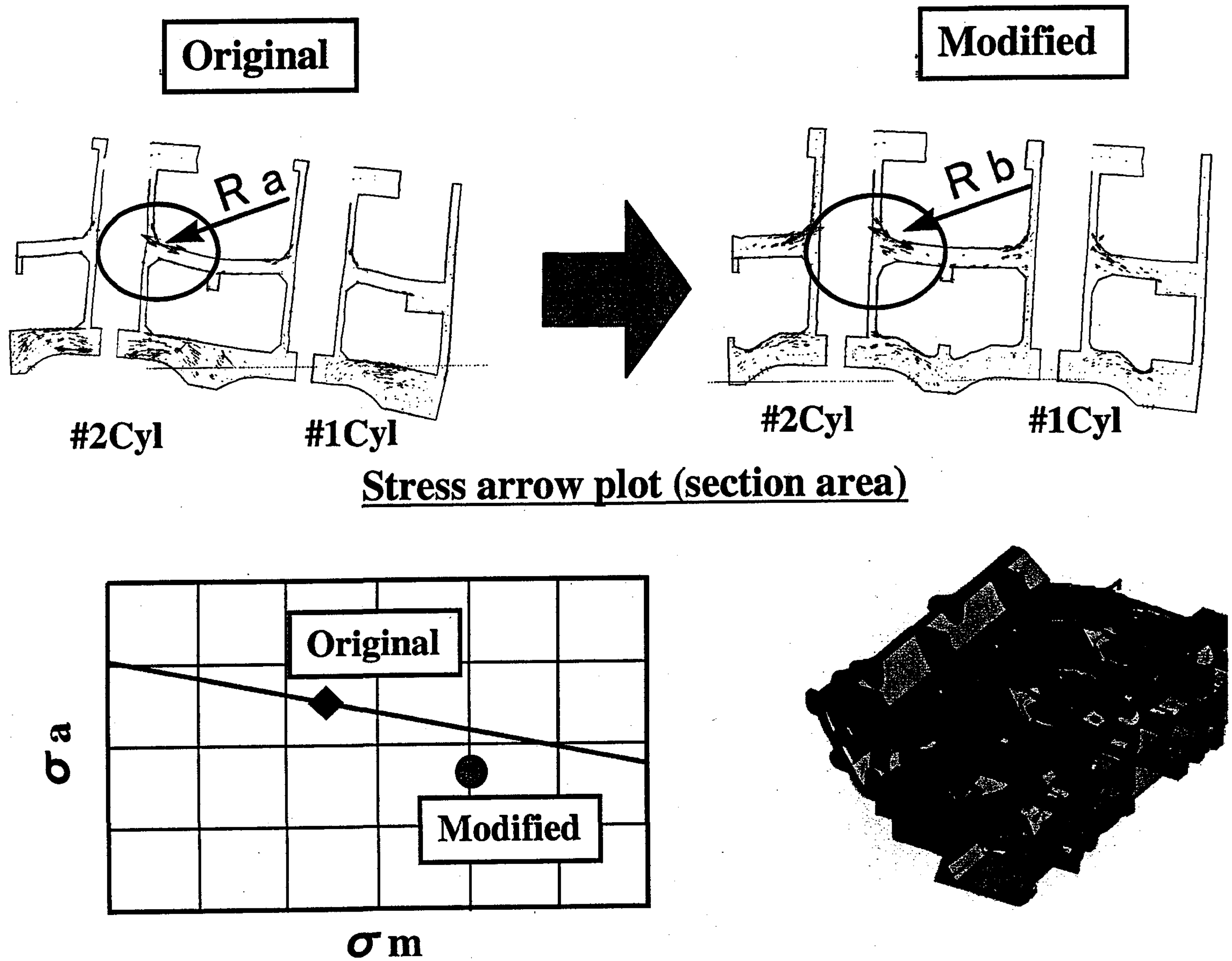

Fig 4. Cylinder Head Stress for each configuration

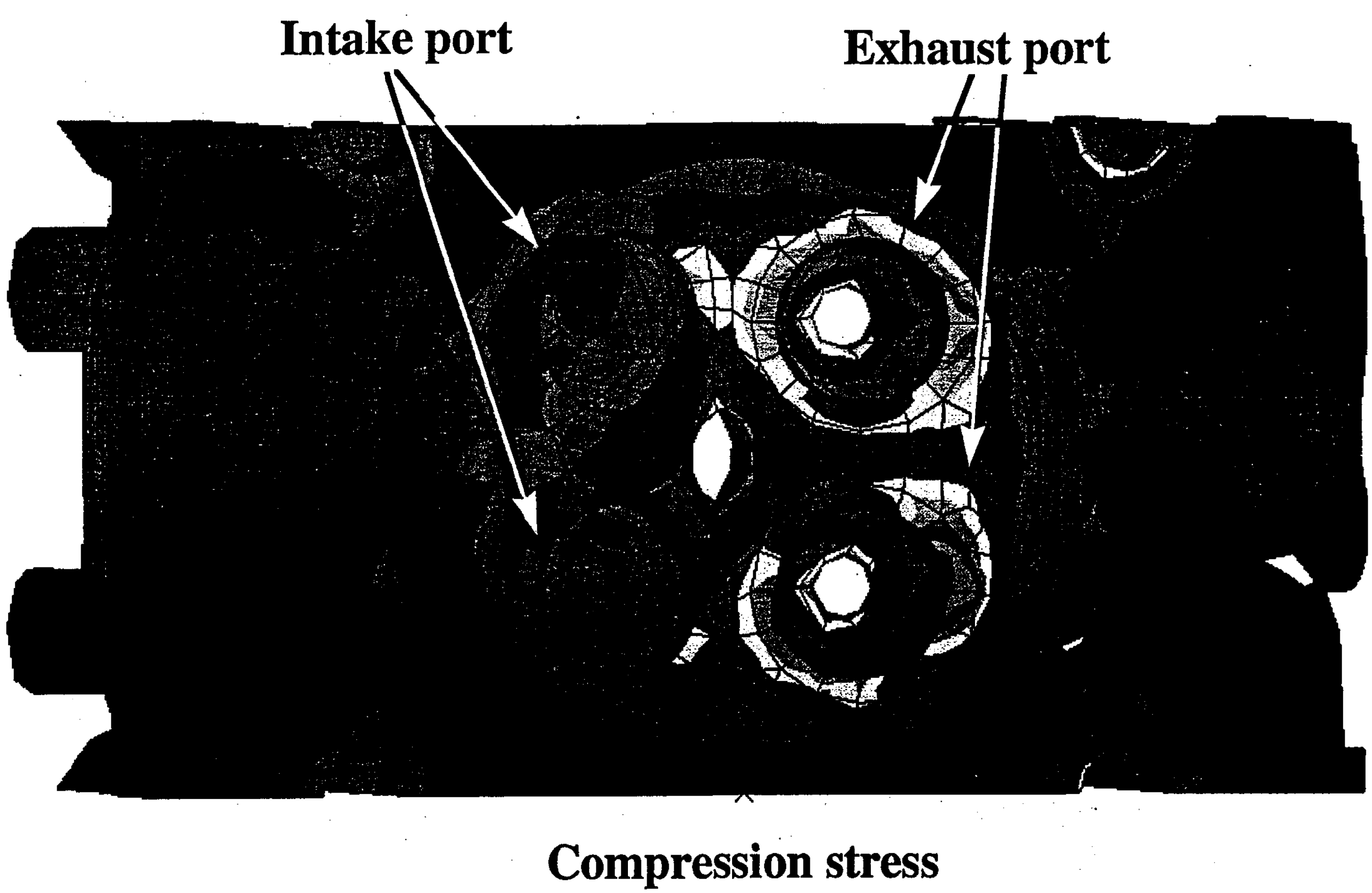

Fig 5. Predicted Thermal Stress of the Cylinder Head

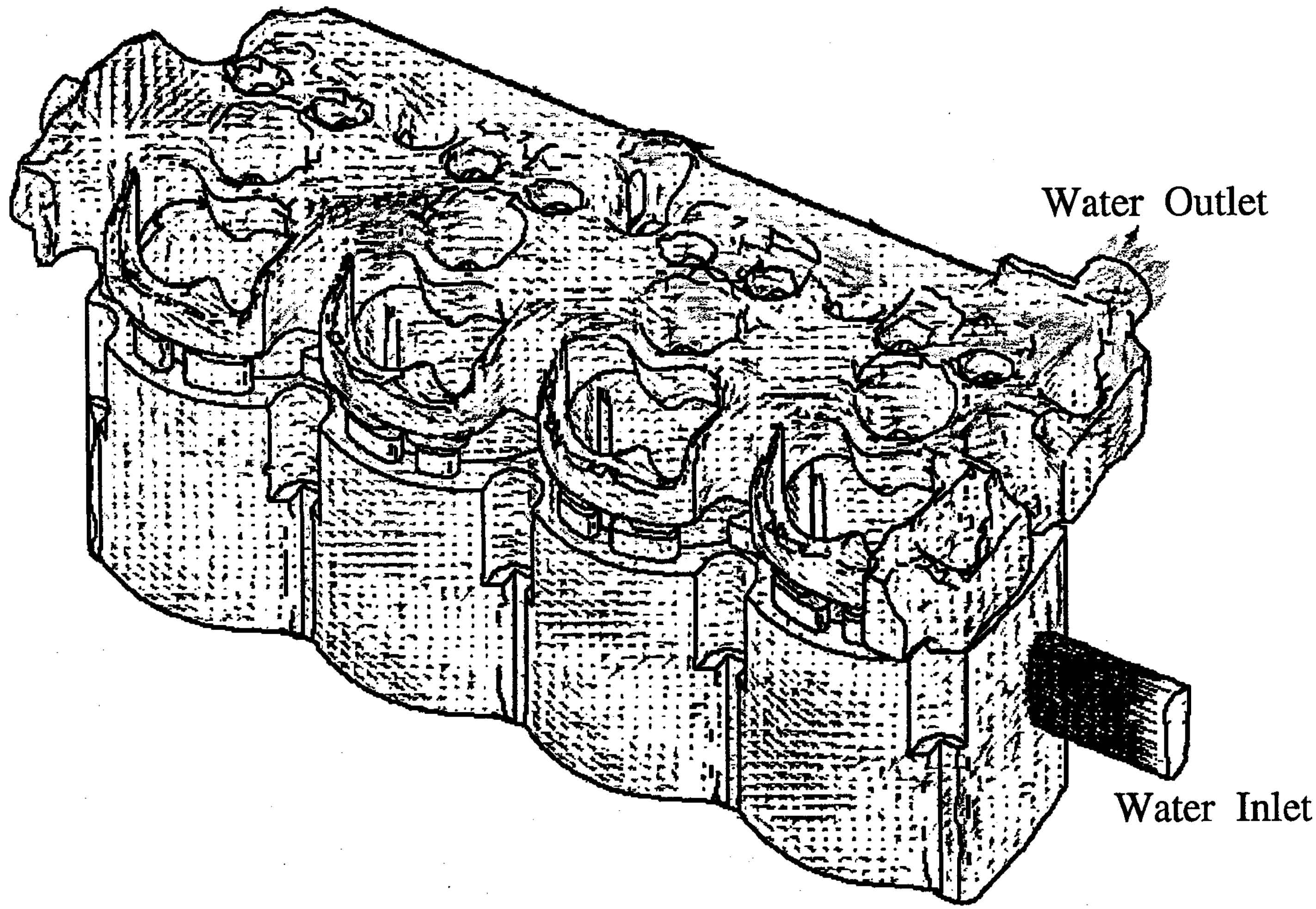

Fig6. Example of Water Jacket CFD result
: surface velocity field

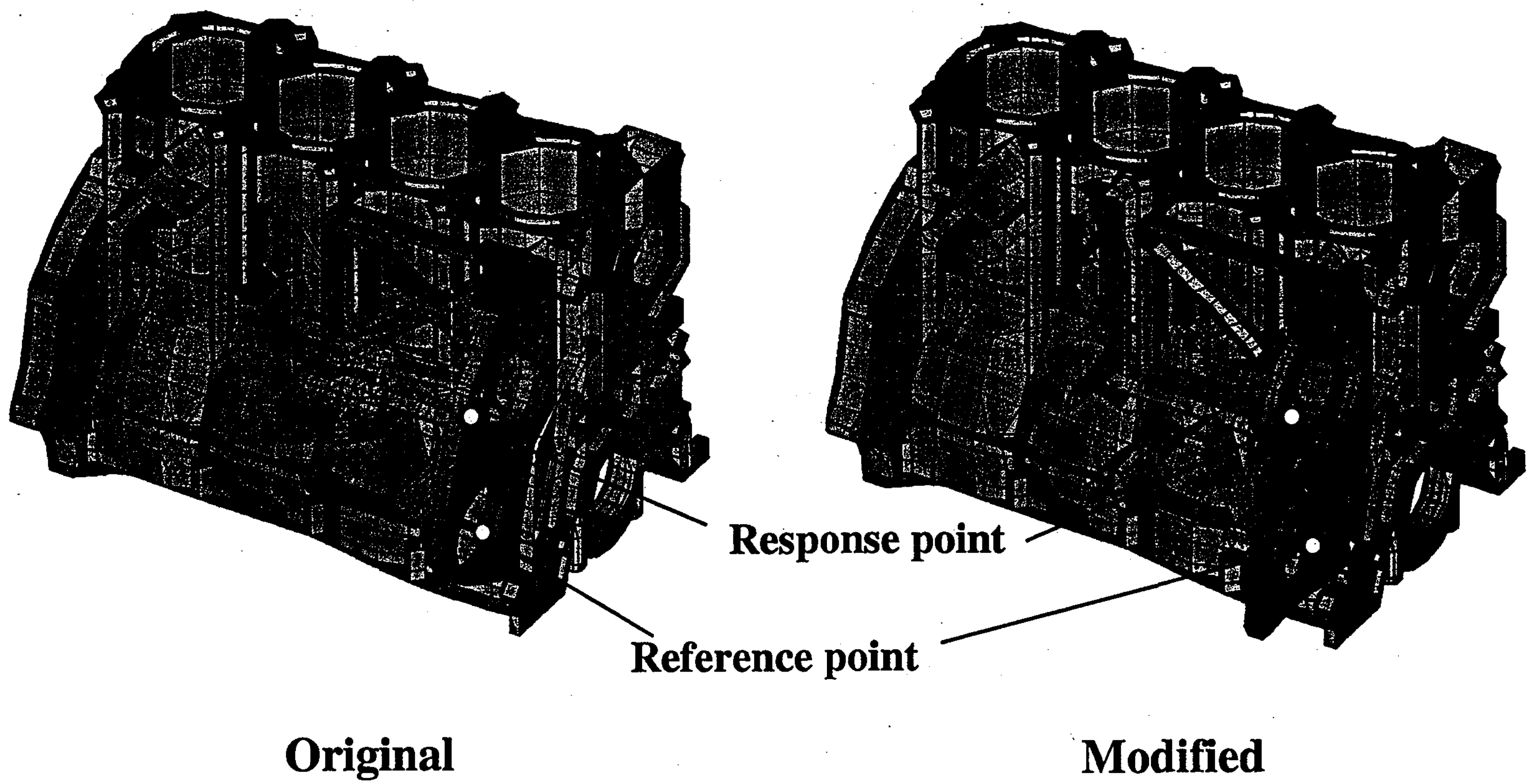

Fig7. FE-model of Cylinder Block, Injection and Vacuum Pump Bracket

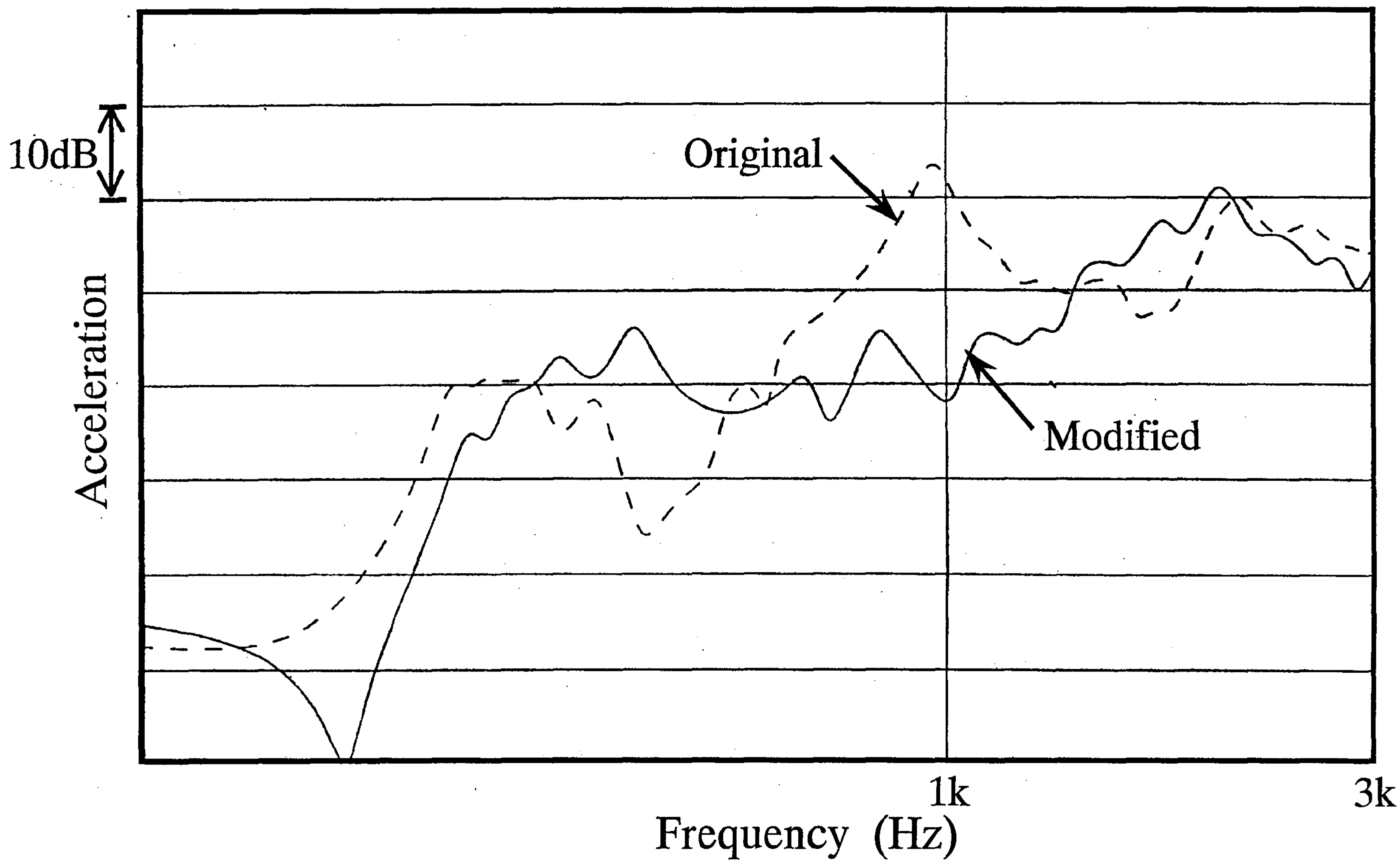

Fig8. Comparison of Accelaration levels