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Invited Paper

OPTIMISATION OF A CONCRETE BLOCK FOR A DIESEL-AGGREGATE

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ABSTRACT

A way to use finite element method (FEM) to create an FE-model of an entire aggregate, total mass 100-700 ton, is presented in this paper. The aggregate consists of a medium speed diesel engine and an alternator, which have been mounted to a concrete block. The whole system can be mounted flexibly or rigidly to the ground.

Usually international standards do not take into account elastic natural frequencies of the concrete block when defining the dimensions. That is why these structures are in many cases over dimensioned. The rapid development of the digital computers have however brought new possibilities to calculate big and complex structures beforehand. In this context the exact dimension is very important because a combustion engine has many excitation frequencies and most of them are not allowed to be near a natural frequency.

The methodology of realistic modelling of a big aggregate using finite element method is described in this paper. The natural frequencies of the structure can be calculated with the achieved model. Also the static and dynamic stresses and responses for given excitations are computed. On the basis of the results the concrete block can be optimised by which noticeable cost savings can be achieved.

The results of calculations and the realistic FE-model were verified by measurements on complete aggregate in the field. The measurements were carried out by using servo-hydraulic shaker, by which the natural frequencies and mode shapes of the concrete block could be found. Also the operational deflection shapes and responses were measured. The calculated values correspond to the measured ones very well.

1. Introduction

Usually international standards do not take into account the elastic natural frequencies when defining the dimensions of the concrete block. That is why these structures are in many cases over dimensioned. Neither do these standards take into account engines which are isolated from the surroundings with a flexible mounting, like rubber elements, steel springs or air cushions. The energy transmission to the surroundings can be minimised with these elements. Also a fear of difficult and expensive repairing has caused to over dimensioning.

Two different types of aggregates were studied. In the first type the engine is mounted flexibly and the alternator was mounted rigidly to the concrete block. The concrete block can be mounted flexibly or rigidly to the ground. The other type of installation is where the engine and the alternator were mounted rigidly to the common base frame, which is isolated from the concrete block by flexible elements, figure 1. The weights of medium speed diesel engines are between 30 ... 250 ton and alternators 10 ...60 ton.

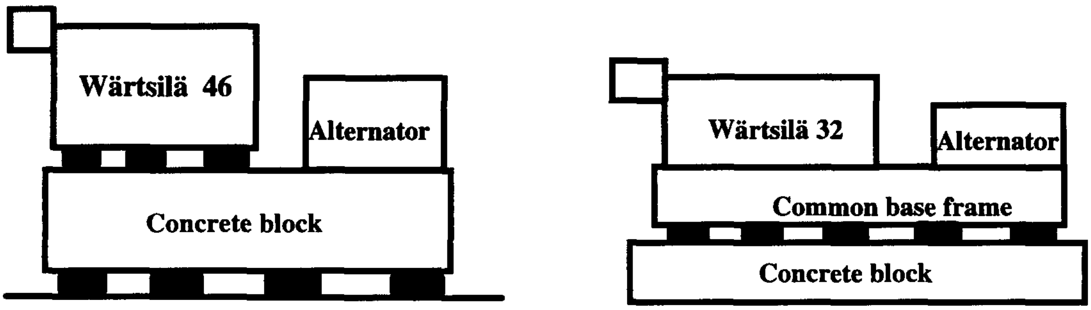

Figure 1: The sketches of the two most typical aggregates.

The results of the calculation and the realistic FE-model were verified by measurements on the concrete block and aggregate in the laboratory of Wärtsilä in Vaasa, Finland. Only full scale measurements can give final confirmation of the reliability of our FE-model no matter how much time and effort the FE-specialist spend. The whole aggregate consists of a four stroke 6L46 medium speed diesel engine, mass 105 ton, the alternator, mass 30 ton and the concrete block, mass 340 ton. The concrete block was designed 10 years ago by using an international standard and that is why it was over dimensioned.

2. Finite element model

To develop a realistic FE-model of the whole aggregate took years by using a step-by-step procedure. In the first step we carried out a frequency analysis of the concrete block. After this a new component was added to the FE-model and a new frequency analysis was carried out. This procedure allowed us to study the influence of the individual components to the dynamic behaviour of the aggregate. After this it was very easy to optimise the thickness of the concrete block. As the final conclusions for our project:" How to model big aggregates" is shown in this paper.

In the first step the concrete block was modelled using 3-D elements. Because the concrete block is isolated by air cushions from the ground the natural frequencies were easy to measure by using modal measurements. The results of the calculated and measured natural frequencies is shown in table 1, which shows that the FE-model of the concrete block is reasonable. The material properties of the concrete block were Young's modulus E= 26 GPa, which corresponds to concrete classification K25-K30, Poisson's ratio ν= 0.1 and density ρ= 2500 kg/m^3. The properties of the concrete can vary a lot of depending on what type of rock material and cement is used. Table 1 gives some limit values for the influence of the properties of the concrete. Classification K10 means poor concrete quality and K40 is better than normally used. The material properties of the concrete can be checked by using modal measurements.

Table 1: The measured and calculated natural frequencies of the concrete block.

classification	K25 measured	K25 FEM	K10 FEM	K40 FEM
lateral bending	45	45	35	50
bending	46	46	35	49
torsion	56	55	39	57

Earlier experience has shown that special attention must be paid to modelling the engine and the alternator and especially to the bolt joints to achieve a realistic FE-model. The solution was found after many trials and errors with FE-calculations and modal measurements. The aggregate has to be modelled so that the lowest elastic natural frequencies and the gravity points of the engine and the alternator correspond to the measured values. This means that the modal measurements on the engine and the alternator have to be carried out before realistic FE-results can be achieved. The lowest natural frequencies of engines are between 25-80 Hz depending on the size of the engine. The engine and the alternator can be modelled quite roughly when the lowest natural frequencies of these components are known. Consequently the amount of degrees of freedom of the FE-model remains in a tolerable level.

If the engine and the alternator are modelled as rigid parts the results of bending and torsion natural frequencies correspond to measured values still quite well, error is less than 15%. The error of the lateral bending can be 40%. However the biggest error appears in the response analysis, which could be even 100%.

The flexible mounting of the engine and the concrete block were modelled with spring elements. The dynamic stiffness of spring elements is shown in table 2. The alternator was fastened by screws to the fixing-rail, which further was fastened to the concrete block. These screws were modelled as flexible joints, which have to be calculated in advance in a separate analysis. The stiffness of this bolt joint is possible to estimate by using FEM. The joint, which is very stiff compared to other structure, is modelled by spring elements. In big engines these joints can be considered as stiff connections.

Table 2: The dynamic stiffness of the flexible elements for our aggregate.

	air cushion kN/m	rubber elements kN/m
axial	475	9216
radial	195	936

The whole FE-model is shown in figure 2. Normally the degrees of freedom of the FE-model are less than 15000. In the FE-model pipe lines are not modelled. The pipes have no influences on the natural frequencies because of flexible bellows but they transmit some forces to the surrounding.

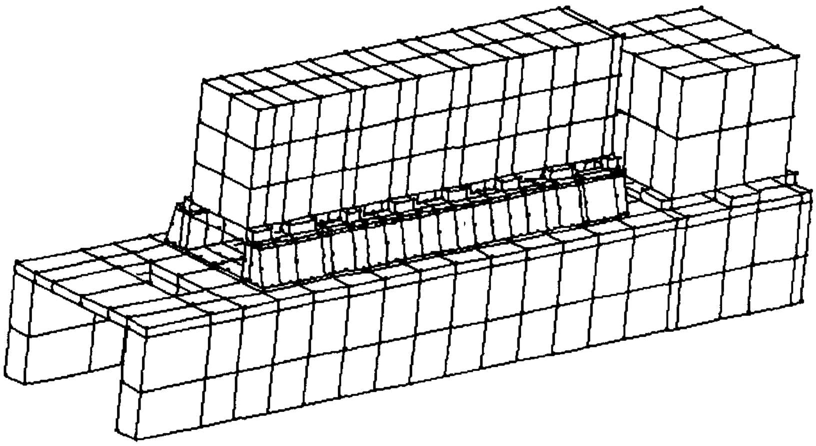

Figure 2: FE-model of the aggregate

3. Measurement of the aggregate

The rapid development of the digital computer have brought new possibilities to measure complex structures. The vibration modes and the natural frequencies have subsequently been determined by modal measurements which in facts has been one the most important reason for continuously increasing popularity of modal analysis technology. The outcome of full-scale measurements will not only tell us how good our FE-model is but it also directly gives us valuable information on behaviour of the structure under the known excitations.

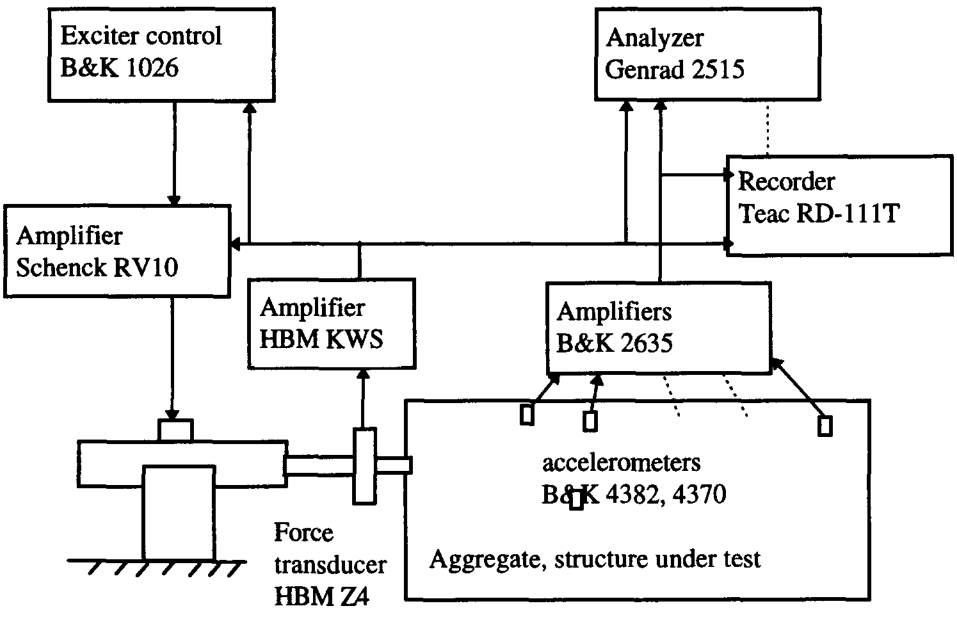

Figure 3: Arrangement of the measurements.

Because the aggregate was very massive and the natural frequencies of the structures were quite low a hydraulic shaker was used to give excitation forces. The frequency range varies from about 0 Hz to 100 Hz. The upper limit depends mainly on the flow rate capacity of the oil pump and the servo valve. In practical application the deflections of excitation point limit excitation forces at high frequencies because of a large displacement of hydraulic cylinder requires a high oil flow rate. The maximum force of the system is about 5000 N. The arrangement of the measurement is shown in figure 3.

4. The natural frequencies of whole aggregate

The measured and calculated natural frequencies of the whole aggregate are shown in table 3. Also the frequencies of the rigid body motion of the concrete block and the engine are shown.

Table 3: The frequencies of rigid body motions of the engine and the concrete block and three lowest deflection modes of whole aggregate.

main motion	concrete block		the engine	
or deflection	measured	FEM	measured	FEM
transversal	0.5	0.6	8.4	7.1
longitudinal	0.8	0.6	3.1	2.6
vertical	1.1	1.1	6.3	6.0
yawing	1.2	0.8	5.6	4.6
rolling	1.3	1.0	2.8	2.8
pitching	1.4	1.0	4.9	4.2
bending	21.9	22.4		
torsion	30.8	29.3		
lateral bending	36.2	38.4		

According to the results of the modal measurements the frequencies of the rigid body motion of the concrete block are very low. Due to the air cushions, also the structure borne noise is extremely low. Table 3 shows that the measured and the calculated values correspond to each other quite well, which indicates that our FE-model is realistic for estimating the natural frequencies.

The results of the FE-model showed some surprises. The engine has no influence to the natural frequencies of the concrete block as long as it has been mounted flexibly. Obviously this is a consequence of the very small stiffness of the rubber elements. This means that the concrete block and the engine are operated separately with very low coupling.

5. The responses

In the FEM calculation the excitation of the six cylinder line engine, Wärtsilä 6L46, was given to the gravity point of the engine. The most important excitations are orders 1, 3 (firing frequency), 4.5 and 6. Table 4 gives the calculated and measured responses at the corner of the engine and concrete block in vertical direction. A typical low frequency response spectrum is shown in figure 4. In the calculations the excitation torque about the crank shaft was 60 kNm, which corresponds to torque of firing frequency, order 3.

Table 4: The calculated and measured responses of the engine and concrete block in unit mm/s (rms).

	measured values				calculated values			
orders	1	3	4.5	6	1	3	4.5	6
engine	2.7	3.2	1.8	1.6	2.0	3.0	0.6	0.8
concrete block	1.0	0.1	0.1	0.1	0.6	≈0	≈0	≈0

As it can be seen the calculated and the measured response values correspond to each other very well. After all the FE-model seems to be realistic and it is possible to use this model to optimise the thickness of the concrete block. Also from the measured values can be seen that the higher orders of the engine excitations is isolated very well by the rubber elements. Results show that even in resonance in worst case the amplitudes on concrete block remain below 2 mm/s if the torque of the firing frequency is used as excitation force. These calculations do not take account the energy transmission through the pipe lines, which in fact is the reason for slight difference between calculated and measured response values.

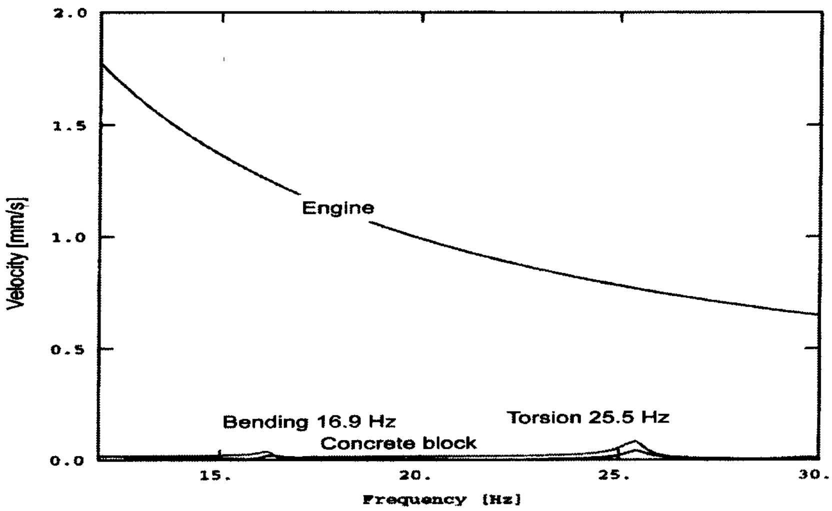

Figure 4: The vibration levels at the corner of the engine and the concrete block at frequency range 10 Hz to 30 Hz at torque M = 60 kNm.

6. Optimisation

When a good FE-model has been created it is very easy to optimise the thickness of the concrete block. What is an acceptable vibration level for concrete block and where should the lowest elastic natural frequencies of the concrete block locate ? It was very difficult to find the international standard or a person able to give information about the acceptable vibration levels on concrete block. After measuring couple of concrete blocks, where the engines were mounted rigidly, it was decided that the overall vibration levels should be below 4 mm/s. Also some standards /4/ indicated that with this level the damages are extremely rare. The natural frequency of the bending should locate near order 1.5, and the natural frequency of the torsion should be a little bit over order 2 corresponding the frequency of 17 Hz. The four stroke engines have external forces and moments at order 1 which have to be taken into account when designing the flexible mounting. Also internal bending moment of order 1 is significant.

With these boundary conditions the thickness of the concrete of 6L46 came to 1.3 meter, which indicates the total mass of the concrete block 160 ton. The original mass was 340 ton.

According to our FE-results the mass of the concrete block should as a role of thumb be approximately the mass of the engine and alternator together. If the subsoil is taken into account the concrete block can be made even smaller.

7. The influence of the subsoil /4/

Two stage elastic mounting systems are very seldom used. Normally the concrete block is mounted to the ground, which has a great influence on the natural frequencies. Also the damping values should increase in this case. When modelling the behaviour of soil under dynamic loads an elastic half-space model is most commonly used. The model assumes that the orbicular foundation is in an elastic half-space. It is also assumed that the soil is infinitely deep and it's behaviour is homogeneous and isotropic. Therefore the natural frequencies of soil can be determined by two coefficients: the shear modules, G, and Poisson's ratio. With this model it is possible to determine the response as a function of time for an arbitrary excitation. Accurate solutions for the response function are derived for each different type of excitation. For this reason the soil can be modelled as a simple mass-elastic approximation where spring and damping coefficients represent the soil properties. In table 5 is shown dynamic stiffness of the sand used in the calculations.

Table 5: Dynamic stiffness of the sand used in calculation /4/

vertical	4800 MN/m	300 000 MNm/rad
radial	3900 MN/m	27 000 MNm/rad

The influence of the subsoil for the lowest elastic natural frequencies of the concrete block is shown in figure 5. The subsoil has great influence to the natural frequencies of the concrete block as was expected. When the subsoil is better than moraine the influence of the thickness of the concrete block becomes insignificant. Furthermore the subsoil has significant lowering influence the amplitudes because of the damping values of the subsoil. In this project we did not optimise the concrete block installed to the subsoil because a lot of subsoil test should be carried out beforehand at the site.

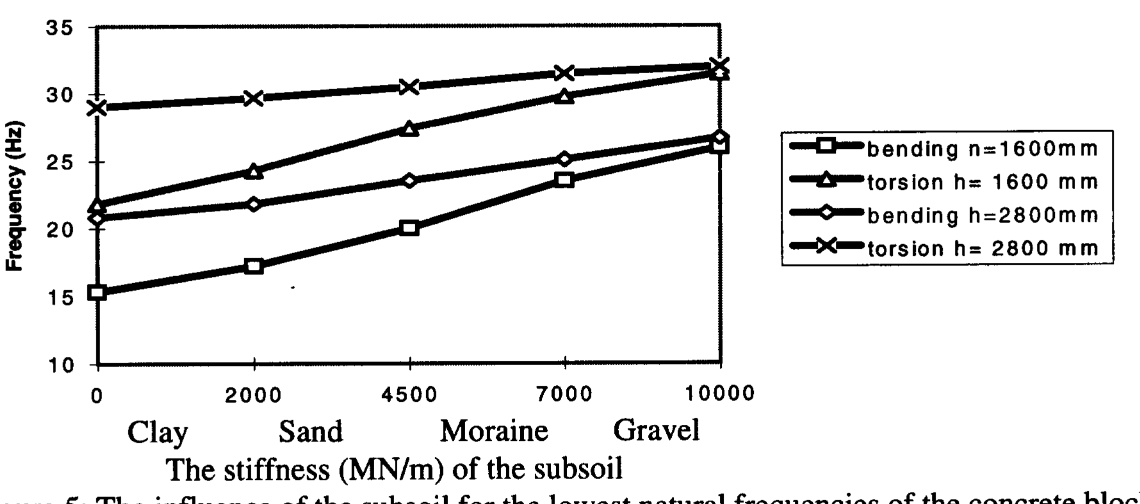

Figure 5: The influence of the subsoil for the lowest natural frequencies of the concrete block

8. Conclusion

The rapid development of the digital computer has brought new possibilities to calculate big and complex structures. In this paper it was shown how to create a realistic diesel-aggregate FE-model which corresponds well to the measured values. The engine and the alternator have to be modelled as elastic structures so that their natural frequencies and gravity points correspond to the measured values. A local FE-model of the bolted joints for the alternator and the engine has been created to estimate their realistic dynamic stiffness.

The lowest natural frequencies of the concrete block of the FE-model correspond to measured values. Also the response analysis gives reliable results.

On the basis of the measured results and with the realistic FE-model the concrete block can be optimised. The mass of the concrete block could be reduced by half which would result in remarkable cost saving. As a role of thumb it can be said that the mass of the concrete block should be about the mass of the engine and the alternator together.

The influence of the subsoil is considerable. If the subsoil is taken into account the thickness of the concrete block can be made smaller.

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