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Division V

VIBRATION STRESS REDUCTION AND MODIFICATION EVALUATION OF JET PIPES ON EMERGENCY DIESEL GENERATORS

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Abstract

Background is that frequent vibration fatigue leakage at location of socket welding connection between small bore jet pipes and run pipes on emergency diesel generators (EDGs) affects normal operation of EDG and needs vibration fatigue stress reduction by modification of jet pipes. The objective is to modify jet pipe for avoiding socket weld leakage at root of jet pipe connection with run pipe and to reduce vibration fatigue stress of jet pipe, ensuring that no leakage due to vibration fatigue occurs and a normal operation of EDG. The method is that a new designed structure of jet pipe verified by a code ruled stress evaluation procedure for different loads like gravity, pressure, measured vibration loads, seismic loads ,is implemented with an in situ vibration stress verification measurement. The result is that both calculated and measured vibration fatigue stress of the new designed jet pipe is much lower than that of the original one and can meet code's fatigue stress requirement. Conclusion is that modification scheme of jet pipe for root socket weld leakage failure, after design calculation verification and site measurement validation, is of prominent effect in reducing vibration fatigue stress and improving fatigue performance of jet pipe, which fulfills modification and evaluation goal of jet pipe leakage for safe operation of EDG.

Key Words: Emergency Diesel Generator, Jet Pipe, Vibration Fatigue, Modification, Evaluation

INTRODUCTION

Vibration fatigue failure of small bore pipes in operation of nuclear power plants(NPPs) occurs usually with a high frequency,which can result in loosening or fracture of some kind of components on valves or equipments, or even breaching pressure boundary of system leading to potential operation hazard.As operation years of NPP units increase,vibration fatigue problem of small bore pipes becomes more and more prominent and is one of the important items for NPP's ten years periods' vibration fatigue safety review from national nuclear safety authority.Usually,those small bore pipes suffered from vibration fatigue failure have an outer diameter of not more than 2 inches and exists in a form of instrument pipes,charge pipes,vent pipes etc.,connected to run pipes or other equipments with a site convenient installation way of socket weld which is usually a constant source of small bore pipe's vibration fatigue leakage.EPRI has ever focused on vibration fatigue failure of socket welds in small bore pipes of NPP and comes with productive suggestions and measures.ASME has also set up a standard and criteria for evaluation of piping vibration.Other countries with NPPs like France and Russia have corresponding standards or allowable vibration limits of piping.

Emergency diesel generator (EDG) in NPP is an important safety equipment.One NPP in China has equipped two EDGs in one unit and thus has a total of 8 EDGs for all 4 units in this NPP. Each EDG is composed of two engines and a generator and is of an equipment layout of one engine in the left side of the generator and the other engine in the right side of the generator. There are many small bore pipes with different functions on these engines suffered vibration fatigue failure, among which jet pipe is a representative one.Both the left and right engines have a jet pipe with the same structure and function suffering vibration fatigue leakage on socket welds, which impairs normal operation and safety maintenance function of EDG and needs a modification evaluation. NPP owner modified the jet pipe with a result of reduction of vibration of the jet pipe but failed to pass ASME code vibration evaluation. To ultimately solve the problem of vibration fatigue failure of the jet pipes, on the request of NPP owner, Nuclear Power Institute of China (NPIC) has carried out vibration measurement,failure factors analysis,numeric computation,modification scheme design and evaluation for these jet pipes ,and validated effectiveness of this modification scheme by post modification vibration stress measurement with a result of passing code evaluation.

1 PIPING DESCRIPTION

Jet pipe(Figure 1) with a design internal pressure of 0.3Mpa,a code nuclear safety class of 3, has a connection to a 6″ run pipe of a dimension ofΦ168.3mm×4.5mm at location of run pipe's underground bend pipe segment. A segment of small bore pipe with an outer diameter of 48.26mm and a material of carbon steel, a valve of a mass of 9.5kg and a height of 260mm, a bellow supported on floor constitute the jet pipe near connection of run pipe. Run pipe with a maximum fluid temperature of 88^{o}C has a leakage at location of socket weld of the jet pipe.

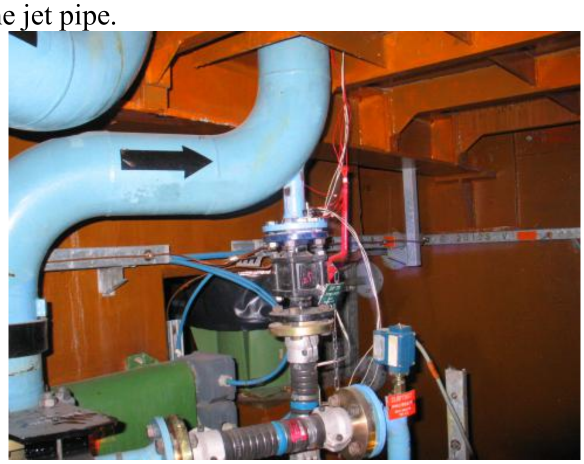


Figure 1. Jet pipe before modification

2 PRELIMINARY MODIFICATION

A preliminary modification of the jet pipe was conducted by the NPP owner, who thought in-coordinate vibration between run pipe and jet pipe was the main cause for large vibration stress of socket welds. A support was added between the run pipe and the valve on the jet pipe to make the two items vibrate more consistently and alleviate end mass of small bore pipe segment of the jet pipe. Two jet pipes of one EDG was first modified by NPP owner with preliminary modification scheme shown in Figure 2, and vibration stress at root of socket weld was then measured with a result that newly added support can have some effect on reducing vibration stress of socket weld, the variance of vibration stress of each jet pipe can still not meet ASME code rules' requirements. Simply adding a new support can not ensure that each jet pipe can pass vibration stress evaluation, thus a further new modification was needed to solve this problem.

3 NEW MODIFICATION SCHEME

The NPP owner commissioned NPIC to fulfill further modification of jet pipe for reducing vibration stress of socket weld to a level that can pass code rule evaluation,after the preliminary modification scheme failed to meet code vibration fatigue stress requirement. An intensive analysis was made by NPIC and three key factors contributing to large vibration stress on socket weld was identified. The first factor is that there was no support on the valve which together with the segment of small bore pipe formed a vibration model of a cantilever beam with an end mass. Elimination of end mass can largely reduce fixed end vibration stress of a cantilever beam, which can be partially realized by adding a support to end mass, the valve,or fully realized by moving the end mass,the valve, to some other location not so near to the socket weld. The second factor is that the jet pipe socket is connected to the run pipe at a location of bend which is a structure with geometric discontinuity leading to high stress concentration, worsening this kind of structure geometric discontinuity and further increasing the socket weld stress concentration factor. The last but not the least factor is that vibration of that type of EDG is always large,which can result in long time vibration fatigue of most of the small bore pipes on the EDGs,among which jet pipe socket weld leakage is just a typical representation due to large EDG vibration. Site acceleration measurement found that the bellow has an efficient vibration reduction effect by comparing larger accelerations on the upper end of the bellow with smaller accelerations on the lower end of the bellow with a magnitude times factor from 5 to 9.Based on the above mentioned analysis of three key factors contributing to large socket weld stress of the jet pipe, a new modification scheme was proposed by NPIC,which suggested moving the valve connected to the small bore pipe segment to a location after the bellow on the pipe line.In other words,the new modification scheme was to exchange the installation position of both the valve and the bellow,and the valve would also be supported. Support added by the NPP owner would be canceled. This new modification scheme eliminated the end mass of the vibrating cantilever beam, and was supposed to have a satisfactory effect on reducing vibration stress at socket welds of jet pipes. The new modification scheme was implemented in such a way that once an EDG jet pipe modification was fulfilled, vibration stress measurement would soon be carried out to make a proof that the modification could successfully meet code vibration fatigue stress requirement.

Figure 2. Preliminary modification scheme

Figure 3. New modification scheme

4 NUMERIC SIMULATION

To support the feasibility of the new modification scheme,numeric simulation with ANSYS was carried out by NPIC,modeling the bend and the small bore pipe segment with shell elements,and the valve and bellow with pipe elements.Fixed constraints were applied at both ends of the bend and the valve.The numeric analysis model is shown in Figure 4.

4.1 *Modal Analysis*

Modal analysis is needed not only for later stress computation of jet pipe by spectrum analysis method,but also to avoid that natural frequencies of modified jet pipe would coincide with that of the actuating EDG frequencies and resonance occurred.After modification,the three frequencies with the largest participation mass are 287.65Hz,294.85Hz,1104.89Hz in X, Z and Y direction ,respectively.The corresponding mode shapes of these frequencies are shown from Figure 5 to Figure 7.Modal results show that the fundamental frequency of modified jet pipe is far higher than the operating 25Hz fundamental frequency of EDG,which can satisfy basic frequency requirement for modification.

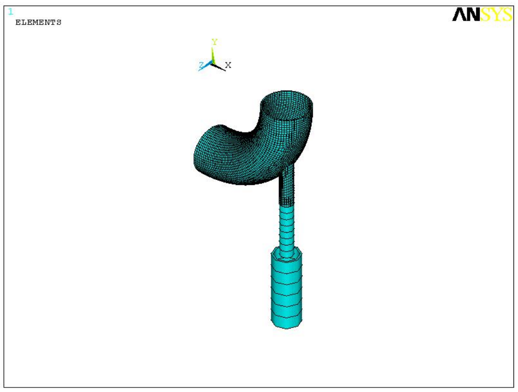


Figure 4. Analysis model of modified jet pipe

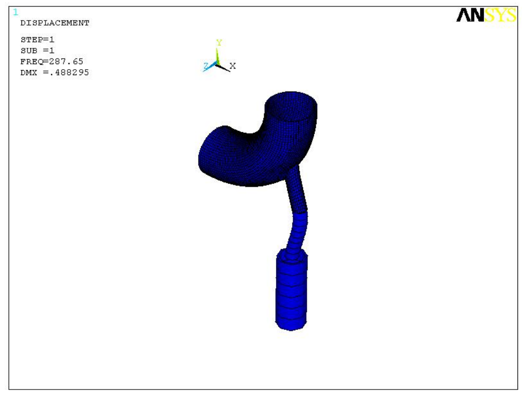


Figure 5. Fundamental Mode shape in X direction

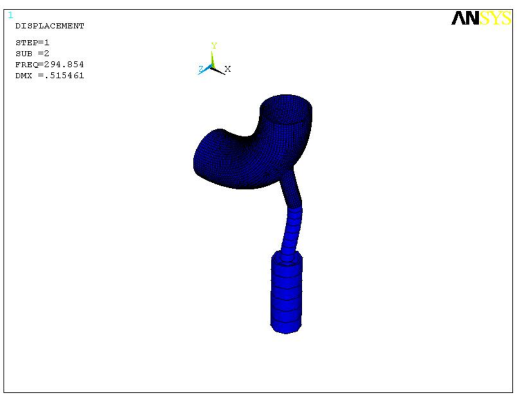


Figure 6. Fundamental mode shape in Z direction

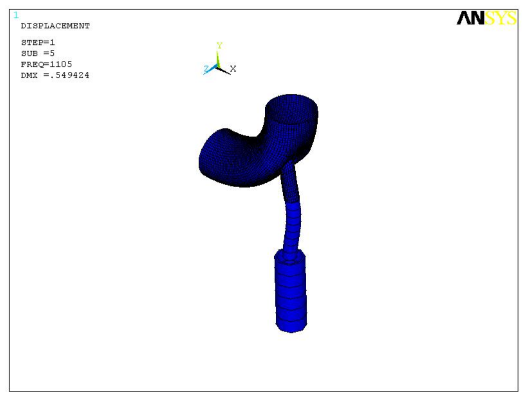
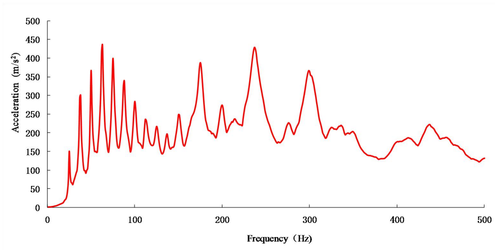


Figure 7. Fundamental mode shape in Z direction

4.2 *Vibration Stress*

Vibration stress was computed to assess fatigue of socket weld of the jet pipe in advance before implementation of the new modification scheme. Spectrum analysis method was used to obtain vibration stress with a modal response combination method of SRSS.Maximum vibration accelerations at 4 junctions of run pipe and jet pipe before modification on 2 EDGs were measured and selected for conversion to acceleration response spectra with a damping ratio of 2% as an input of the vibration stress calculation(Figure 8,Figure 9).Acceleration spectra were enveloped and broadened according to ASME code rules before application.Since frequencies that have a larger contribution to pipe stress are usually below 300Hz, an analysis cutoff frequency 500Hz of acceleration can meet vibration stress calculation demand.There are higher frequencies than 500Hz in the vibration accelerations, so the acceleration spectra will not converge on 500Hz. Spectra values at the cutoff frequency will be used for those with higher frequency values than 500Hz.Vibration cycling number was determined based on three factors,design life span of EDG,fundamental operating frequency of EDG,monthly operation hours.A cycling number of 8.64×10^7 was obtained and conservatively treated as 1.0×10^9 which corresponds to an alternative stress amplitude of 61MPa in ASME S-N fatigue life curve of carbon steel.



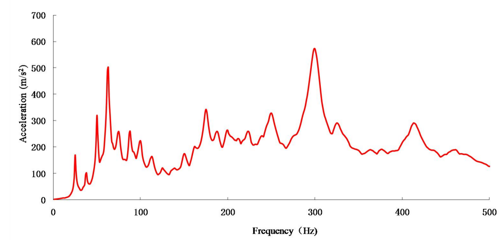


Figure 8. Horizontal acceleration response spectrum Figure 9. Vertical acceleration response spectrum

Calculation result show that maximum stress intensity S_c of the jet pipe at location of socket weld end under vibration load is 37.9Mpa which is converted to an alternating stress amplitude S_a of 43.1MPa after taking into geometric factor and temperature amendment of fatigue curve by Equation (1).

$$S_a = K \times \frac{E_e}{E_c} \times S_c \tag{1}$$

In Equation (1),K is a peak stress concentration factor with a value of 1.1 according to ASME to take local geometric discontinuity at socket weld into account due to shell analysis model simulation inefficiency. E_e with a value 207Gpa from the fatigue S-N curve, E_c working elastic module of a value of 200Gpa.Since the calculated 43.1MPa is smaller than the allowable alternating stress amplitude of 61MPa with a cycling number of 10^9 for carbon steel material, vibration fatigue stress of the jet pipe after modification can meet ASME requirement and the new modification scheme is predicted to have a feasible application.

4.3 *Stress Evaluation*

Jet pipe after modification should also meet code stress criteria under load cases. Loads like gravity, internal pressure, seismic loads and vibration loads were taken into account. Since the fundamental frequency of the jet pipe is higher than 100Hz, equivalent static method was used for seismic analysis. Calculation results shown in Table 1 manifested that the jet pipe after modification can meet code requirements for stresses under load cases.

Table 1: Stress evaluation of jet pipe under loads cases(MPa)

Level	Loads	Membrane stress	Allowable membrane stress	Membrane plus bending stress	Allowable Membrane plus bending stress
O	Pressure,Gravity	22.30	1.0S=103	25.56	1.5 S=154.5
A	Pressure,Gravity Vibration	53.06	1.0S=103	61.91	1.5 S=154.5

Level	Loads	Membrane stress	Allowable membrane stress	Membrane plus bending stress	Allowable Membrane plus bending stress
B	Pressure,Gravity Vibration,OBE	53.16	1.1 S=113	62.21	1.65 S=170
D	Pressure,Gravity Vibration,SSE	53.25	2.0 S=206	62.50	2.40S=247

5 TEST VERIFICATION

Vibration stress and acceleration at the same measurement location before and after modification were compared to verify modification plausibility.For stress measurement, root position near the socket weld is of larger stress and was bonded 4 strain gauges along axial direction of the jet pipe with an even separation circumferential angle of 90°. Accelerations on flange of the jet pipe small bore pipe segment was measured before and after modification.Since the EDG operates at different powers,vibration stress would vary with EDG operation power. It's manifested that measured vibration stress increases with EDG power,as shown in Figure 10,which suggests a full power load case of EDG operation as the measurement load case for vibration stress measurement. Vibration acceleration in Table 2 and vibration stress in Table 3 at full power load case of EDG make a proof that the new modification scheme of the jet pipe effectively reduces jet pipe vibration.Maximum measured vibration stress,a value of 36.6MPa,is closed to the former calculated stress value 37.9MPa.Calculated results are usually a little bit more conservative due to input load envelope and spectra value broadening than the measured value.After a further correction of measured stress according to above mentioned Equation (1), measured alternating stress amplitude reaches a value of 41.7MPa,a little bit smaller than the same way amended calculation value of 43.1MPa,and is also within the allowable code limit of 61 MPa for fatigue stress with a certain margin,which demonstrates plausibility of the new modification scheme.After a successful modification of 2 jet pipes on 1 EDG,the same kind of modification was carried out on the rest of 14 jet pipes of the other 7 EDGs with same type, in a sequential way of modification and proof testing. All the total 16 jet pipes have a vibration stress lower than ASME code allowable fatigue stress limit.

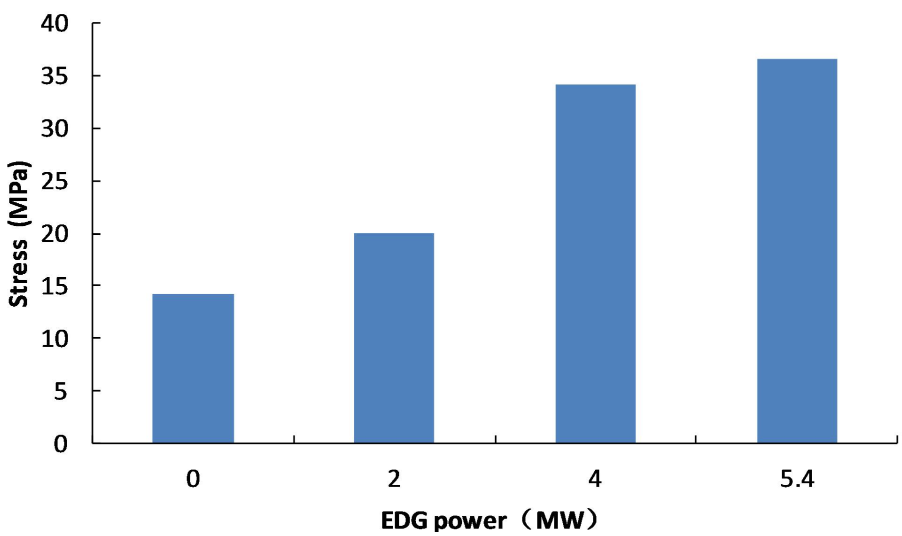


Figure 10. Variance of vibration stress with EDG power

Table 2: Accelerations on flange of jet pipe

Direction	Before modification (m/s^2)				After modification (m/s^2)			
	Maxima of left side jet pipe	RMS of left side jet pipe	Maxima of right side jet pipe	RMS of right side jet pipe	Maxima of left side jet pipe	RMS of left side jet pipe	Maxima of right side jet pipe	RMS of right side jet pipe
Axial direction of EDG	112.7	25.5	99.1	24.9	13.8	3.1	19.8	4.0
Tranverse direction of EDG	124.3	28.0	91.1	20.4	8.9	2. 6	15.3	4.5
Vertical direction of EDG	70.1	15.7	97.8	26.9	9.4	2.4	18.3	5.3

Table 3: Vibration stress at root of jet pipe

Jet pipe position	Measurement position	Alternating stress amplitude (MPa)	
		Before modification	After modification
Right side	Right side at root of jet pipe	13.17	23.38
	Back side at root of jet pipe	24.13	11.19
	Left side at root of jet pipe	43.13	36.58
	Front side at root of jet pipe	32.07	11.32
Left side	Right side at root of jet pipe	98.16	18.20
	Back side at root of jet pipe	58.70	13.28
	Left side at root of jet pipe	20.37	19.17
	Front side at root of jet pipe	27.39	12.50

6 CONCLUSIONS

After a failure of preliminary modification scheme solving vibration fatigue leakage problem of jet pipe socket weld, a detailed and specific analysis was carried out to find out factors leading to large vibration stress of the jet pipe,based on which a new modification scheme was proposed with a satisfactory vibration stress reduction and a code conforming load cases stress values.After a tentative modification of the jet pipe according to the new scheme showed a success and gained a close measured vibration stress with the calculated one, a sequential modification was carried out with proof test on all the other jet pipes of the rest of EDGs.Modification results support the efficiency and plausibility of the new modification scheme of the jet pipe.In a word,conclusions are drawn as follows:

(1) Both improper structure layout of the jet pipe and large vibration of EDG are dominant factors contributing to vibration fatigue leakage of jet pipe socket weld;
(2) The new modification scheme,validated by both numeric calculation and test measurement results,can effectively reduce vibration stress of jet pipe socket weld;
(3) Vibration stresses obtained by way of numeric calculation and test measurement are of reasonable coincidence;

(4) All the 16 jet pipes on 8 EDGs in the NPP modified with the new modification scheme have a vibration stress value that can meet ASME code requirement.

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