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SLENDEREX: USING SHEAR7 FOR ASSESSMENT OF FATIGUE DAMAGE CAUSED BY CURRENT INDUCED VIBRATIONS

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ABSTRACT

This paper focuses on the evaluation of the fatigue damage caused by current induced vibrations on the SlenderEx system. SlenderEx is a low cost drilling system being evaluated by Petrobras for fast appraisal of exploratory wells. Shear7 is the well-known computer program developed by MIT for assessment of fatigue damage on slender offshore structures (such as cables and risers) caused by vortex induced vibrations (VIV) originated from sheared currents.

The SlenderEx system consists of a 13-3/8 inch 72 lb/ft casing connecting the mud line to a semi-submersible platform and is planned for drilling exploratory wells in water depths up to 1800 meters. At the lower end the casing penetrates some 400 meters into the soil and the upper termination is a stress joint located under the surface BOP which is guided by a frame placed at the moonpool region. Tension is provided by conventional tensioning system.

Fatigue damage is firstly evaluated for a set of variables defined as the Base Case. After that a parametric study is conducted for the determination of the influence of main parameters on the response. This study is warranted by the uncertainties about input parameters. The investigation consists of a parametric variation of current velocity, riser tension, lock-in bandwidth, single/multi-mode response, and stress concentration factors.

A total of 88 current profiles and the corresponding probabilities of occurrence are considered in the analysis. Some of the current profiles are originally non-planar. The current velocities have then to be projected onto a plane for being analyzed with Shear7. The differences arising from this limitation are also evaluated.

INTRODUCTION

Petrobras is investigating the use of the SlenderEx Drilling Riser System for floating drilling operations in up to 1800 meters water depth, Campos Basin, offshore Brazil. The SlenderEx Drilling Riser System is distinguished by its use of 13-3/8-in casing pipe as the drilling riser (which is cemented into the seafloor well), the absence of seafloor equipment (i.e., no seafloor emergency disconnect) and the surface support of the Blow-Out Preventer (BOP), see Fig. 1. The philosophy of the system is similar to the SX system which has been used by Unocal in Indonesia.

With applied top tension of 900 kips and 10 ppg drilling fluid, the riser system's allowable offset for the floating platform is approximately +/- 7% WD (in survival conditions) or greater in the 1-year Storm Events, thus exceeding (1) the station keeping allowable offset of 4% WD and (2) the riser stroke's allowable offset of 5.3% WD, with or without the presence of Vortex-Induced Vibrations. It was concluded that the riser system's Operating Envelope is limited by the station keeping system and available riser stroke, not the performance of the riser system itself.

One of the main concerns about the technical feasibility of the system was the amount of fatigue damage due to vortex induced vibrations (VIV) originating from the ocean currents. The casing threaded connectors have a Stress Concentration Factor (SCF) as high as 4. Reuse and redeployment of certain portions of the 13-3/8-in pipe proved to be acceptable from a fatigue damage viewpoint, provided that the threaded pipe connector could take repeated make-and-brake operations without damage while maintaining integrity of structure and pressure.

The focus of this paper will be on the SlenderEx system fatigue damage due to vortex induced vibrations originating from the ocean currents. The accumulated fatigue damage is evaluated for a configuration defined as Base Case and after that a parametric study is conducted for assessment of the main variables influencing riser response.

THE CURRENT PROFILES

A total of 88 current profiles and their probabilities of occurrence were considered in the analysis. Some of them were originally non-planar and it was necessary to project them onto a plane for the VIV analysis through Shear7. The origin of the 88 profiles is as follows: there are 8 main directions (N, NE, ... NW) and within each main direction there are 11 sub-profiles, given a total of 8x11 = 88 profiles. Some of these have null current velocities however the procedure was done like this for the sake of standardization. The current profiles and probabilities of occurrence are presented at Table 1. The number between parentheses is the identification of the profile.

The current profiles were derived from a database originating from an comprehensive measurement program which took place some years ago at Campos Basin. For each of the 8 main directions (N, NE, ..., NW) eleven classes of surface current velocities (0.0-0.1), (0.1-0.2), ... (1.0-1.1) m/s were chosen to adequately represent the environment. The surface current and its direction dictated the percentage of occurrence of the so-called sub-profile. The remaining current velocities along the water column were derived from statistics of simultaneous occurrences associated with the surface value (in time and direction).

THE BASE CASE

The Base Case is defined in Table 2. Some of the input data to Shear7[1] were taken as suggested at the User's Manual, i.e, allowing the program to choose. The effective tension at the mud line (x/L=0) is 100 kips. The linearly varying effective tension of 1045 N/m refers to the 13-3/8 inch casing only whereas the 224.6 kg/m mass per unit length in air encompasses the 13-3/8 inch casing and the 5 inch drill pipe and the 10 ppg drilling fluid at the casing/drill pipe annular and inside the drill pipe. The external added mass .was considered through the definition of the added mass coefficient as 1.0. The maximum damage occurred for joint 4 at x/L = 0.0151 and the resulting damage was 0.0543 for 1 year (the resulting fatigue life is 1/0.0543 = 18.4 years). The Base Case is a single mode analysis. All damages are expressed in terms of 1/years units.

Figure 2 shows the participation in response of the main current profiles for the Base Case. Not all 88 profiles are shown, only 24 profiles were chosen such as they represent 90% of the number of occurrences. The participation of those profiles in response represents 93% of total damage for joint number 4 at x/L = 0.0151 (close to the mud line). It is worthwhile to point out that due to the non-linear characteristics of the VIV problem, some unexpected results are likely to occur, which makes the choice of the number of current profiles for analysis very difficult.

From Figure 2 it is possible to conclude that most part of damage is contributed by profiles with low probability of occurrence. Conversely a current profile with very low probability of occurrence can produce a significant fatigue damage. Therefore the better policy is to run all load cases and accumulate the damage contributions from all the current profiles.

RANGES IN THE INPUT PARAMETERS

A parametric study is conducted for some selected parameters. They are varied around the defined Base Case figures. They are current velocity, bottom effective tension, lock-in bandwidth, single/multi-mode response and stress concentration factor. Some input data are not varied, such as the Strouhal number, which is taken as 0.17. For vibrating cylinders at sub-critical Reynolds numbers, the Strouhal number varies between 0.14 and 0.18.

Current velocity, bottom effective tension and stress concentration factor are changed ±10% around the Base Case. The 10% figure represents the uncertainty about the value. The two-sided lock-in bandwidth is 0.38 for the Base Case and was changed to 0.45. A broader reduced velocity range increases the correlation length for each mode's power-in region. The bandwidth may be very broad for low density cylinders in uniform flow. In sheared flow this is not the case and the bandwidth should be much smaller.

EFFECT OF 10% UNCERTAINTY W.R.T. CURRENT VELOCITIES

The velocities of all 88 current profiles were multiplied by 0.90 and 1.10 and the resulting damages are compared with the Base Case, see Figure 3. All input data with exception of current velocities remain the same. Figure 3 shows the damage along the region 0<x/L<0.05, i.e., in the vicinity of the mud line, which is the region with highest damage. For the 3 cases the joint with highest damage is #4 (x/L = 0.0151) and the resulting damage ratios are 0.0281, 0.0542 and 0.0809 for the 90%, Base Case and 110% cases respectively. It is worthwhile to point out that in this case a reduction of 10% in the current velocities led to a decrease in total damage of around 50% (0.0281/0.0542 = 0.52). Again, the sensitivity of VIV response to the input parameters is remarkable.

The current profiles with highest participation in total damage were #53 (21%), #41 (23%) and #52 (27%) for the 90%, Base Case and 110% cases respectively. Their probabilities of occurrence are 0.46%, 2.43% and 1.31% respectively.

EFFECT OF 10% CHANGE IN THE BOTTOM EFFECTIVE TENSION

The effective tension at mud line (x/L=0) was varied around the Base Case value, considering 90% and 110% of the nominal figure of 100 kips. All input data with exception of minimum effective tension remain the same. Figure 4 shows the damage along the region 0<x/L<0.05, i.e., in the vicinity of the mud line, which is the region with highest damage. For the 3 cases the joints with highest damages are #4 and #5 (x/L = 0.0151 and 0.0201 respectively) and the resulting damage ratios are 0.0672, 0.0542 and 0.0311 for the 90%, Base Case and 110% cases respectively.

The current profiles with highest participation in total damage are #52 (21%), #41 (23%) and #7 (18%) for the 90%, Base Case and 110% cases respectively. Their probabilities of occurrence are 1.31%, 2.43% and 0.09% respectively. It can be seen that a increase of 10% in tension causes the total damage to become 57% (0.0311/0.0542 = 0.57) of the nominal Base Case value.

EFFECT OF CHANGING THE TWO SIDED LOCK-IN BANDWIDTH

The two sided lock-in bandwidth was changed from 0.38 (Base Case) to 0.45 in order to assess its effect on riser response. Figure 5 shows the total damage along the riser due to the 88 current profiles in the neighborhood of the mud line (0<x/L<0.10). Joint 4 (x/L=0.0151) is again the joint with the highest damage and the change in bandwidth causes the damage to increase from 0.0542 to 0.0708 (31% increase).

SINGLE MODE AND MULTI-MODE RESPONSE

In order to compare the Base Case results with a multi-mode response, the cut-off parameter was set to 0.02. Therefore all modes potentially excited are identified and used in the response calculation. The Base Case had only the mode with the maximum available input power from the fluid included in the response, therefore the program was forced to a single mode lock-in evaluation.

Besides that the multi-mode reduction factor now was input as 0.8, allowing the response to be reduced to account for an overestimation of the lift coefficient.

Figure 6 shows the total damage along the riser due to the 88 current profiles close to the mud line (0<x/L<0.10). Joint 5 (x/L=0.0201) is the joint with the highest damage and the change in the mode cut-off and multi-mode reduction factor causes the maximum damage to decrease from 0.0542 (Base Case) to 0.00656 (a factor of 0.12). The current profile with highest participation factor in total damage (42%) is #7, which has only 0.09% of probability of occurrence.

For current profile #7, mode #17 (period=3.4 sec) has the highest input power ratio, followed by mode #5 (period = 11.8 sec). Input power ratio for mode #5 is 0.22.

In Shear7, the maximum input power and the corresponding mode is first identified. The input power for each potentially excited mode is then divided by this maximum input power, resulting in an estimated input power/maximum input power ratio. If this ratio for a particular mode is less than the cutoff value, this mode will be excluded in the subsequent calculation.

The cutoff parameter lies in the $0 < cutoff \leq 1.0$ range. For preliminary runs it should be set to a small number such as 0.02, allowing all modes potentially excited to be used in the response calculation. When set to 1.0, the program is forced to a single mode lock-in calculation. For a small value of cutoff, the power levels of the various possible responding modes are identified.

Physically, the input power to maximum input power ratio gives what kind of cylinder response behavior is likely to occur: a single mode or a multi-mode response. If several modes have a comparable input power to maximum input power ratio, then a single mode response may not occur. If there are two or more modes with an input power ratio greater than, for example, 0.9 then single mode lock-in is not likely.

EFFECT OF 10% CHANGE IN SCF

For the S-N curve defined by one line segment of the form $N \times S^n = K$, where n = 4.38 for the X API curve, a change in the SCF from SCF_1 to SCF_2 causes the total fatigue damage to be multiplied by a factor of $(SCF_2/SCF_1)^{4.38}$. Therefore an increase of 10% in SCF results in damage multiplied by 1.52, whereas a decrease of 10% in SCF results in damage multiplied by 0.63.

EFFECT OF ALL PARAMETER VARIATION ON TOTAL FATIGUE DAMAGE

Table 3 shows the contribution of each parameter variation on total fatigue damage for the most loaded joint along riser length, which occurs nearby the mud line, at joint 4 or 5 (x/L=0.0151 or x/L=0.0201), depending on the load case. The total damage variation can be as high as 210, considering all the parameters variation acting either favorably or unfavorably.

CONCLUSIONS

- Vortex Induced Vibration is a complex phenomena and it is very difficult to foresee how the various current profiles will contribute to total fatigue damage. Current profiles with very low probability of occurrence may yield significant damage. Conversely a current profile with significant probability of occurrence may produce negligible damage.

- The best policy is to work with environmental data which is as detailed as possible, and to evaluate the fatigue damage originating from all the profiles available.

- Response is highly non-linear. A parametric variation on the main variables influencing the response is also desirable, in order to establish the bounds of the problem. A sensitivity study will help define the safety margins.

ACKNOWLEDGEMENTS

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REFERENCE

1. Shear7 version 3.0 User's Manual, October 1999, MIT

Table 1 – Identification of current profiles (...) and percentages of occurrences

Dir.	Sub-profiles										
	1	2	3	4	5	6	7	8	9	10	11
N –1	(1) .10	(2) .26	(3) .31	(4) .20	(5) .11	(6) .17	(7) .09	(8) .05	(9) .00	(10) .00	(11) .00
NE - 2	(12) .13	(13) .25	(14) .35	(15) .36	(16) .14	(17) .09	(18) .06	(19) .03	(20) .01	(21) .00	(22) .00
E – 3	(23) .22	(24) .43	(25) .51	(26) .52	(27) .39	(28) .25	(29) .12	(30) .04	(31) .00	(32) .00	(33) .00
SE – 4	(34) .43	(35) 1.67	(36) 3.32	(37) 4.36	(38) 4.26	(39) 5.53	(40) 4.31	(41) 2.43	(42) .76	(43) .19	(44) .02
S - 5	(45) .20	(46) 3.68	(47) 11.69	(48) 15.97	(49) 14.28	(50) 10.86	(51) 4.86	(52) 1.31	(53) .46	(54) .12	(55) .00
SW –6	(56) .18	(57) .38	(58) .88	(59) .86	(60) .49	(61) .33	(62) .10	(63) .00	(64) .00	(65) .00	(66) .00
W – 7	(67) .16	(68) .16	(69) .05	(70) .03	(71) .02	(72) .01	(73) .00	(74) .00	(75) .00	(76) .00	(77) .00
NW –8	(78) .14	(79) .16	(80) .12	(81) .07	(82) .09	(83) .02	(84) .03	(85) .00	(86) .00	(87) .00	(88) .00

Table 2 – Base Case input data

Pinned-pinned beam	
1	flag to choose structural model,nmodel
0	flag to choose SI (0) units
199	#of segments in the structure
1810.00	cable total length, meters
0.339725	cable outer diameter, meters or inches
0.3397,0.3136	outer & inside diam. stress material, m
1025.4181	fluid density, kg/m**3
1.55040e-6	kinematic viscosity of the fluid, kg**2/s
224.6515732	cable mass or weight per unit length in air, kg/m
1.0	added mass coefficient
444970.	minimum tension, Newton
2.10E11	Young's modulus, N/m**2
1.7901E-04	moment of inertia, m**4
1045.	linearly varying tension, N/m
0.17	Strouhal no.
6, .00102, 101	Current 1800.0 m WD
.000, various	x/L, vel. (m/s)
0.003	structural modal damping (fraction of critical damping)
0	flag 1 for controlling damping computation (0=program decides)
0	flag 2 for controlling damping computation (0=program decides)
0.4	lift coefficient
0.0,1.0,0.1	response locations (begin, end, and step size), x/L
1	number of SN-curve line segments
0.0	cutoff stress range (N/m**2 or ksi)
1.0E8 2.E6	stress range (N/m**2), cycles to failure point 1
1.981E8 1.E5	stress range (N/m**2), cycles to failure point 2
4.0	global stress concentration factor
0	#of local stress concentration positions
0.38	two sided lock-in bandwidth
0	open .cat file? 0 = no, 1 = yes
0	flag to choose lift coeff. (0=program decides)
0	no. of VIV suppresion regions (0=off)
1	Calculation option, NCAL =1 is full response
1.0 0	Mode Cutoff(0.0 to 1.0), #of user specified modes
1.0 9.806	multi-mode reduction factor, accel of gravity(m/s^2)

Table 3 – Effect of parameter variation on fatigue damage

Parameter variation	Total damage for 88 current profiles			Ratio
	Favorable	Base Case	Unfavorable	(Unfor./Favor.)
Current velocity (± 10%)	0.0281	0.0542	0.0809	2.88
T_{eff} @ x/L=0 (± 10%)	0.0311	0.0542	0.0672	2.16
Lock-in bandwidth (0.38-0.45)	0.0542	0.0542	0.0708	1.31
Single mode/multi-mode	0.00656	0.0542	0.0542	8.26
SCF (± 10% around 4.0)	0.0341	0.0542	0.0824	2.42
All factors simultaneously	0.00142	0.0542	0.299	210

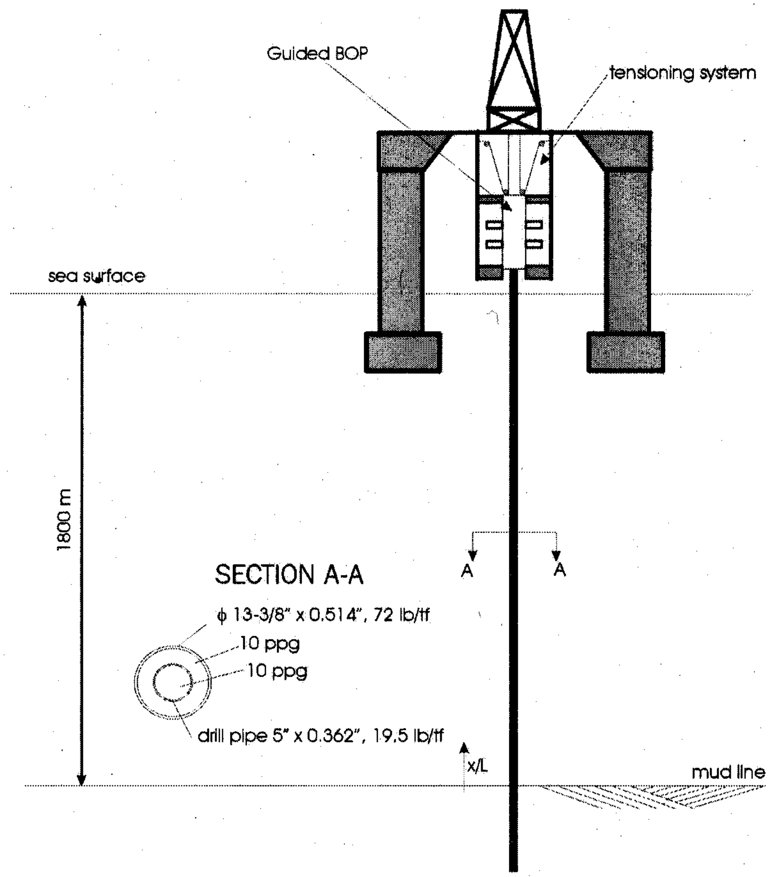

Fig. 1 – The SlenderEx system

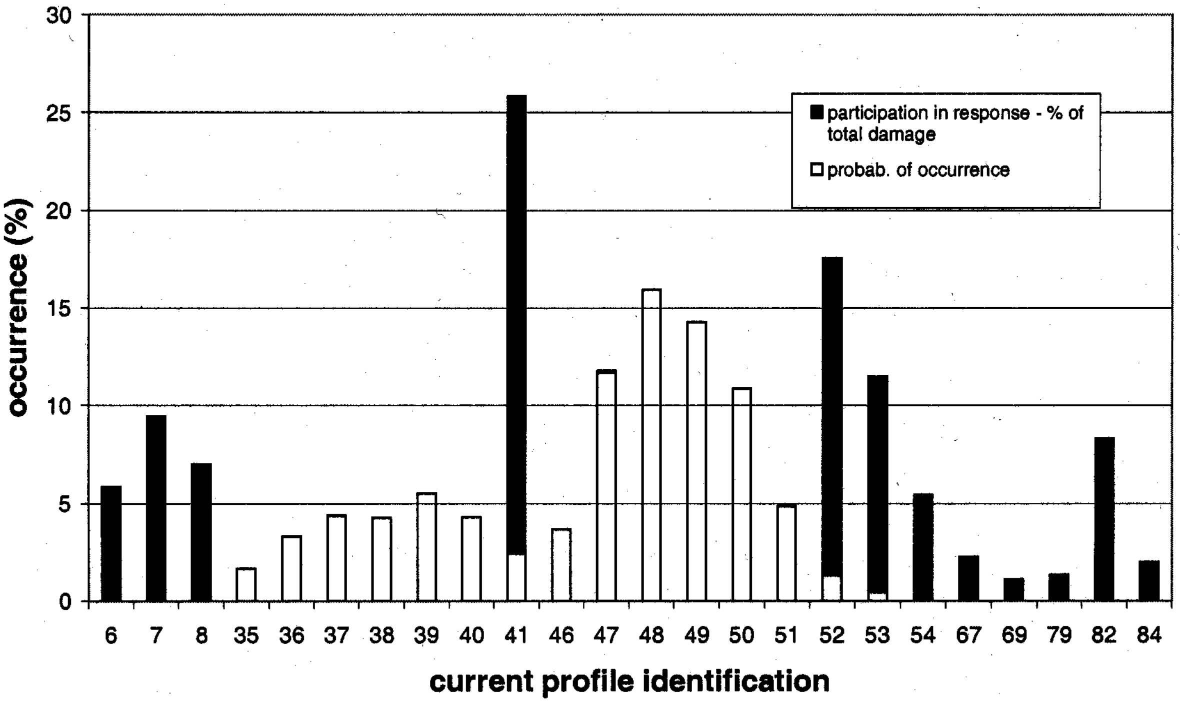

Figure 2 – Probability of occurrence versus participation in response – Base Case

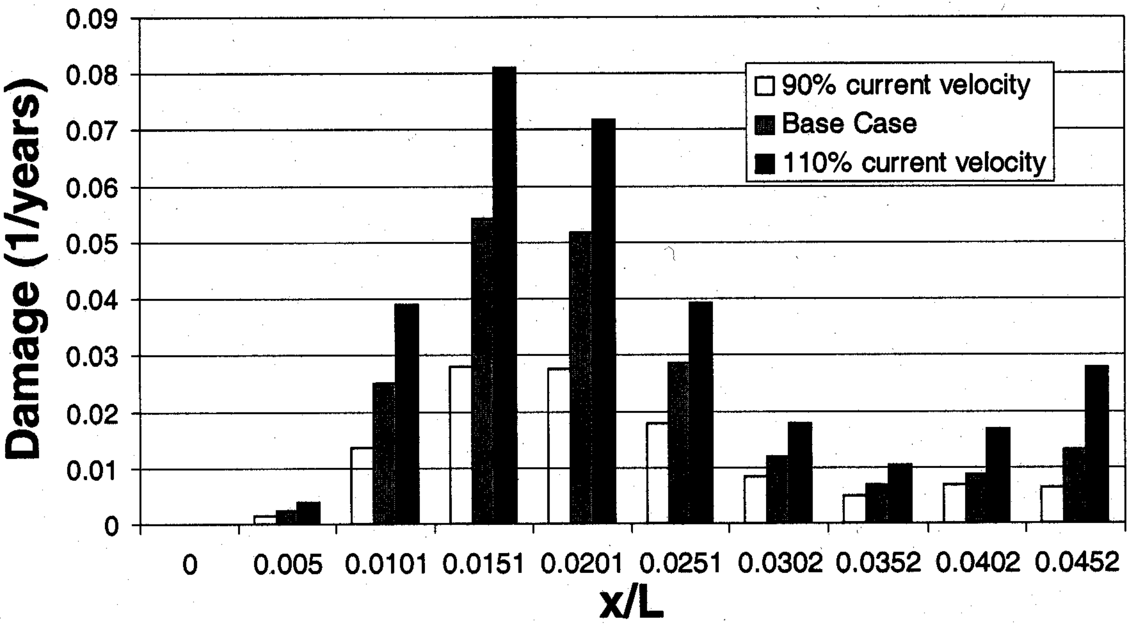

Figure 3 – Effect of 10% variation of current velocities

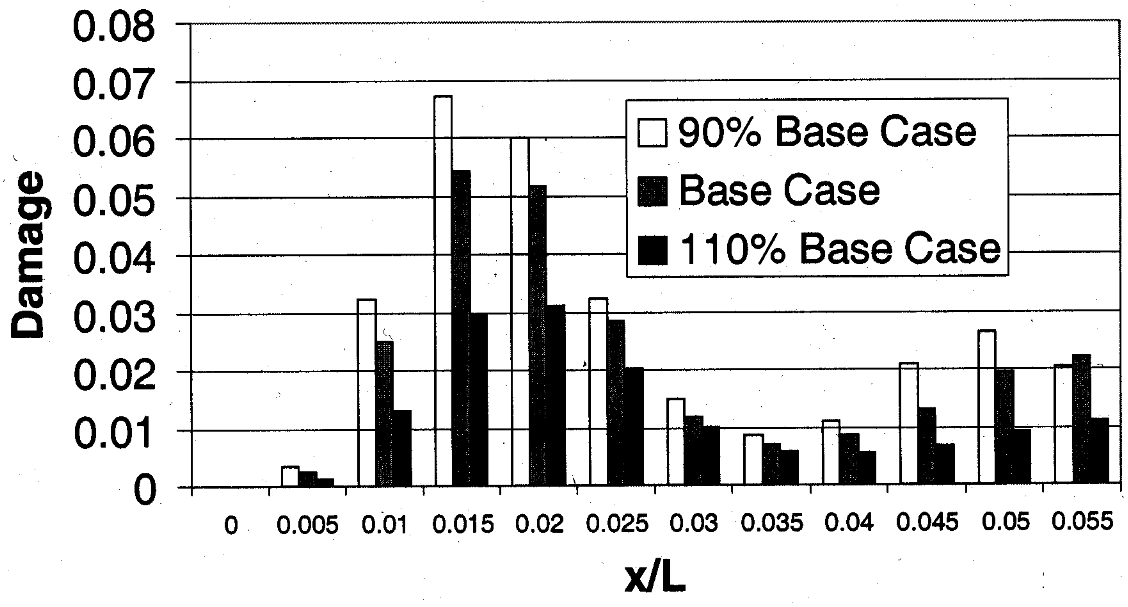

Figure 4 – Effect of 10% variation of effective tension @ mud line

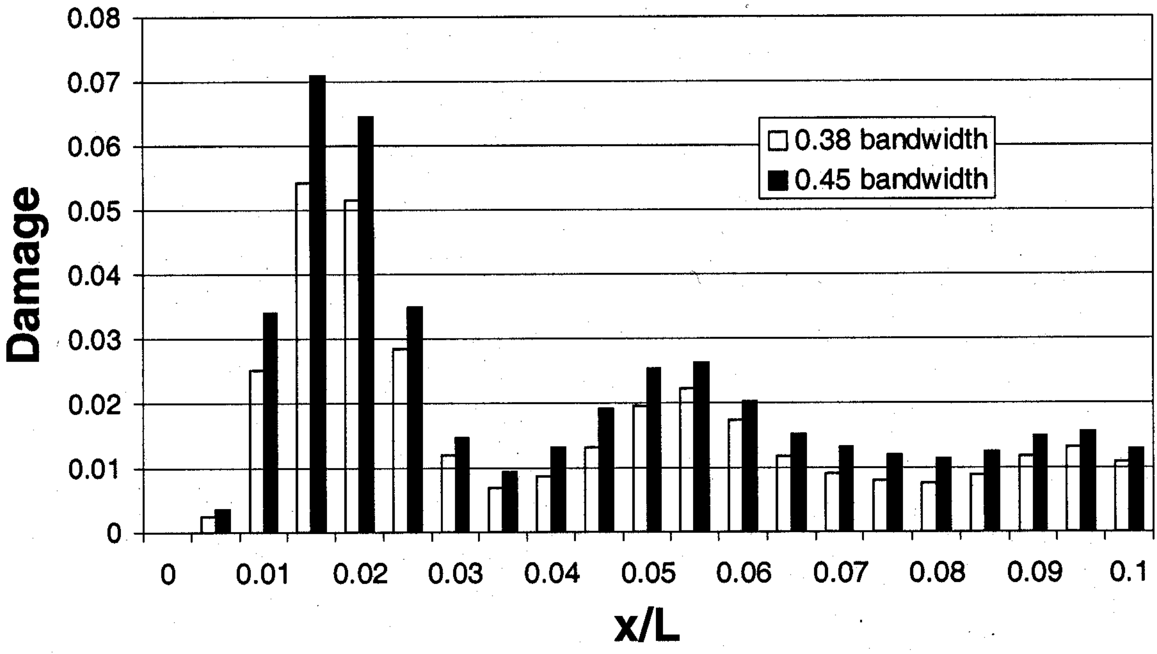

Figure 5 – Effect of variation on lock-in bandwidth

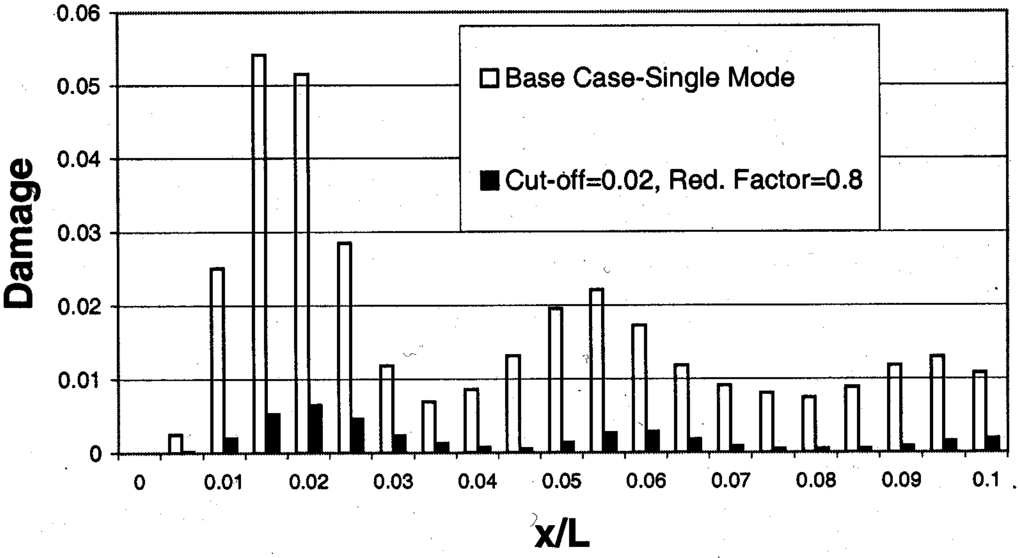

Figure 6 – Comparison between single mode and multi-mode