6. MODIFIED PROCEDURE FOR TRANSFORMATION OF STRUCTURAL RESPONSE SIGNALS TO ICE FORCE TIME-HISTORIES

6.1 General

The previous studies led to the conclusion, that sequences of regular, fully developed steady-state resonance vibrations are decisive for most design purposes, in the case that the ice-structure conditions are likely to generate such vibrations. It was also concluded, that, in most cases, the conditional probability of fully developed resonance is rather high, once a structure is susceptible to ice-induced vibration. Thus, resonance is likely to occur within a broad range of ice conditions, including varying ice drift velocities.

Based on this conclusion, the analysis of global ice forces can now be focused merely on sequences of steady-state vibrations. For such sequences, the accuracy of the transformation between measured structural response and global ice force time-histories can then be improved in the following respects.

* All the modes of the structural vibrations can be considered, in the response functions as well as in the derivation of the relationships between the responses and the ice forces. (In the previous model the latter procedure was based on an approximation, neglecting other than the fundamental, predominant mode, notably the mode that governs the ice-structure interaction.)

* The transformation procedure becomes more straightforward and transparent, since several steps of the previous procedure can be omitted. Thus, the ice force functions can be derived directly from the acceleration signals, after Fourier-transformation. Step-wise integration of irregular signals is avoided. Integration errors need not be a concern as in the previous work.

* A FE-model, processed by means of a comprehensively tested commercial computer code, can be used for the mathematical processing of the signal transformation. The compliance between a measured accelerogram and the derived ice force time-history can then be demonstrated by applying the latter function as a load input to the FE-model.

As indicated above the novel procedure for transformation of measured responses to ice forces takes advantage of the fact that, during a sequence of steady-state resonance vibrations, a sine load generates a sine response with the same frequency. The components of free vibrations, with frequencies closely to the eigenfrequencies of the structure, are thus essentially damped out, when the vibrations stabilize into steady-state oscillations. Then, each sine component $F_n = F_{n\,max} \cdot \sin(\omega_n t + \Theta_n)$

of the load corresponds to a response component, e g acceleration, as follows:

$$\ddot{x}_n = \ddot{x}_{n\,max} \cdot \sin(\omega_n t + \phi_n)$$

Therefore, once the amplitude and phase relations between the load and the response have been determined by means of an accurate model of the ice-affected structure, these quantities can be used for transformation of any sinusoidal acceleration to the corresponding sine load.

Thus, two main tasks can be distinguished between. The first concerns the derivation of relationships between sinusoidal unit loads and responses for the particular structure, the responses of which are measured. This can be performed once and for all for a particular structure such as the NORSTRÖMSGRUND lighthouse. Secondly, each individual record of measured response signals have to be processed by Fourier analysis and transformed into ice force time-histories, employing the structure-specific relationsships between amplitudes and phases. The two phases of the work are described and illustrated by examples in the following.

6.2 Amplitude and phase relations between acceleration and ice force sine components

6.2.1 Calibration of the FE model

The FE-model, developed during Phase 1 of the ice force study, was adjusted (stiffnesses and masses) so that a reasonably good agreement was obtained between its modal frequencies and the eigenfrequencies of the lighthouse structure (Figure 6:1). The latter quantities can be identified in the power density spectra of the measured acceleration records. Most clearly, the modal frequencies can be distinguished in records of mainly free vibrations, but the peaks representing the eigenfrequencies are also visible in other records, as indicated in Subsection 6.2.3.

The following points are of major importance in the modelling of the structure:

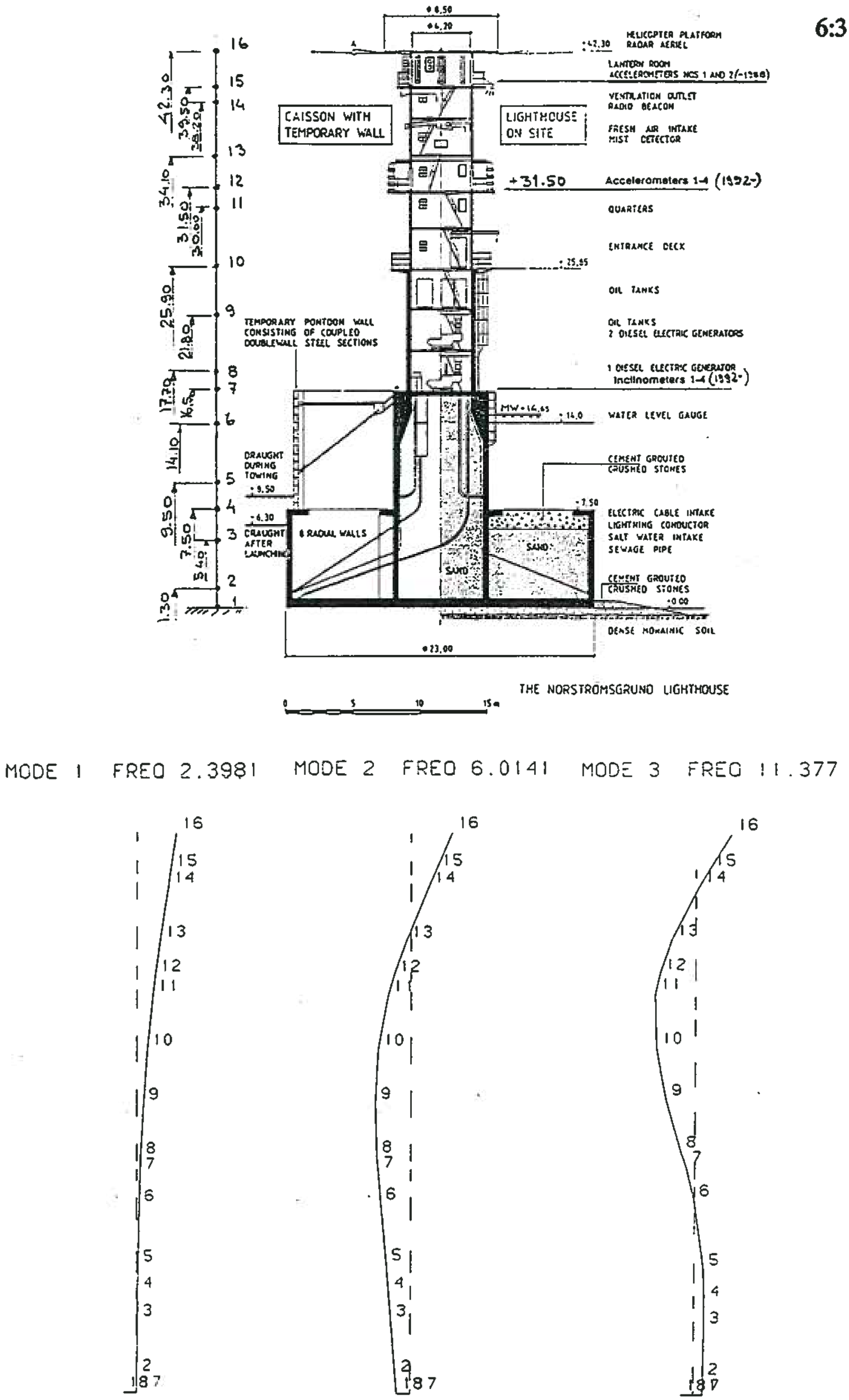

Figure 61

The FE-model and its significant modes of vibration

- The true modal frequencies and modal shapes, at least in the proximity of the measurement points, must be simulated with a very good accuracy. Since the fundamental eigenfrequency f_1 governs the frequencies f_n of all the load components, it is important primarily to obtain the correct ratios between each modal frequency f_k and f_1. A small deviation between the true f_1 value and that of the model can be tolerated only the ratios f_k/f_1 are correct.

  In our case we accepted $f_1 = 2.40$ Hz in the model, whereas the true frequency is normally around 2.35 Hz. This difference does not affect the derivation of amplitude and phase relations. Only, when demonstrating the ice-structure interaction by applying a derived load time-history to the model, this difference has to be accounted for by adjustment of the sine components of the load to fit $f_1 = 2.40$ Hz instead of the measured frequency 2.35 Hz.

- The modal damping, particularly that of the first mode, must also be determined with a good accuracy, since it strongly governs the amplitudes of the resonance vibrations and, though of less importance, the phases.

In principle, the modal damping can be determined for each mode that can be distinguished (by filtering) within the selected sequence(s) of free vibrations. Among other records of essentially free vibration, one of those displayed in Figure 6:2 (from March 28, 1988) may serve as an example.

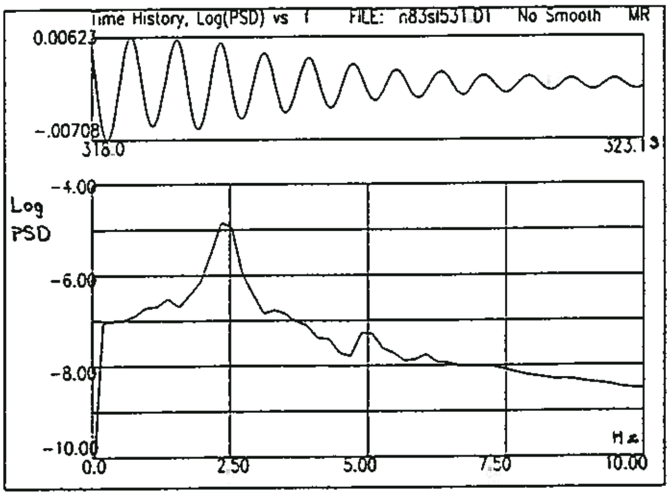

Figure 6:2

Displacement time-history from March 28, 1988, with sequences of essentially free vibrations

For the predominant **1st mode** the damping can be determined directly from the recorded accelerogram as follows:

$$c/c_{crit} = \frac{1}{2\pi} \cdot \ln \frac{m}{\Sigma \ddot{x}_i/\ddot{x}_{i-1}}$$

where m is the number of cycles and $\Sigma \ddot{x}_i/\ddot{x}_{i-1}$ is the sum of ratios between m consecutive amplitudes.

Thus, for the time period from 319 to 322 seconds, the average damping was obtained as follows.

$$m = 5:\ c/c_{crit} = \frac{1}{2\pi} \cdot \frac{1}{0{,}809} = 0{,}034$$

Previously, damping ratios between 0.036 and 0.050 have been observed. The most probable value is 0.040 ±0.005, possibly including some "ice damping", due to friction against broken fragments of ice, for instance.

6.2.2 Determination of acceleration amplitudes and phases for unit sine loads

The following instruction applies to the derivation of amplitude and phase relations.

(1) Apply unit sine loads to the FE-model

$F = 1 \cdot \sin n\omega_1 t$ with $n = 1\text{-}5$

(2) For each sine load determine the acceleration sine functions for steady state vibrations of modes 1, 2 and 3 individually and for all the modes vibrating together. 3 instrument levels are investigated. The response acceleration functions are defined by amplitude maxima and phase angles:

$$a_{nk} = a_{nk\,max} \cdot \sin(n\omega_1 t + \varphi_{nk})$$

n are load component numbers
k are mode numbers

$a_{nk\,max}$ and φ_n are thus determined for

$n = 1\text{-}5$ and
$k = 1\text{-}3$ and for Σk.

See Figure 6:3: Responses of the FE-model and its eigenmodes to unit sine loads $n = 1\text{-}5$.

The amplitude values $a_{n\,max}$ and phase angles φ_n for the common response of all the modes are listed in Table 6:1.

Sine load No n	Acceleration amplitude per 1 MN load amplitude (m/s^2)	Phase angle φ_n (radians)
1	4.30	1.511
2	1.04	6.261
3	0.57	3.318
4	0.13	3.274
5	0.07	3.419

Table 6:1

Responses to unit sine loads: Acceleration amplitudes and phase angles in node No. 14. Responses of all the nodes k = 1-3 taken together.

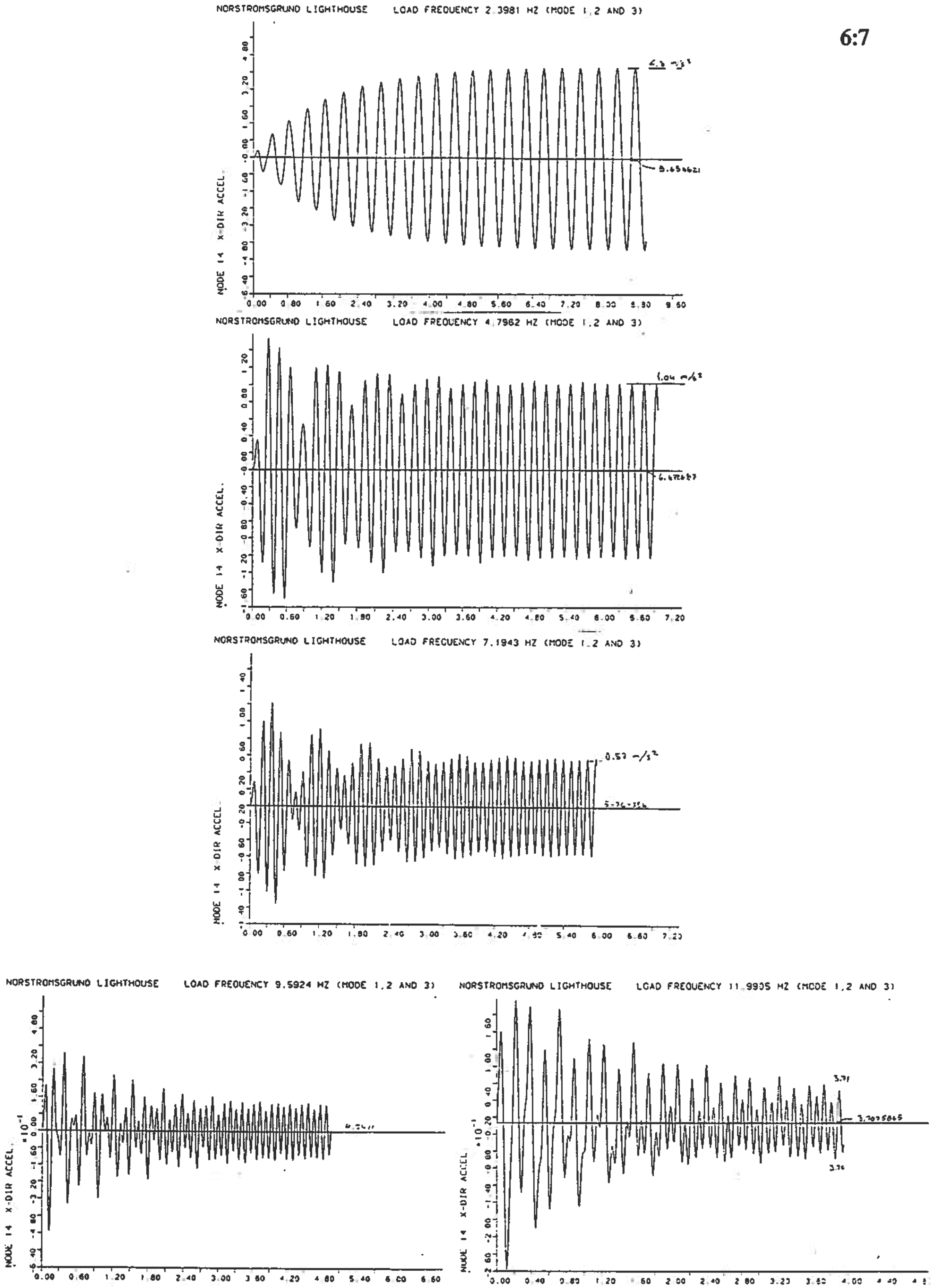

Figure 6:3

Responses of the FE-model to unit sine loads n = 1-5

6.2.3 Transformation of acceleration records to ice force time-histories

Based on an acceleration record from March 28, 1988 (File No. N83S-M051) the transformation procedure is here described step by step and illustrated by plotted outputs from the computer calculations.

(1) Input acceleration record

In Figure 6:4 the selected accelerometer signal No. 1 (Direction N-S) at level +39.5 (Model Node 14) is displayed together with its Power Density Spectrum.

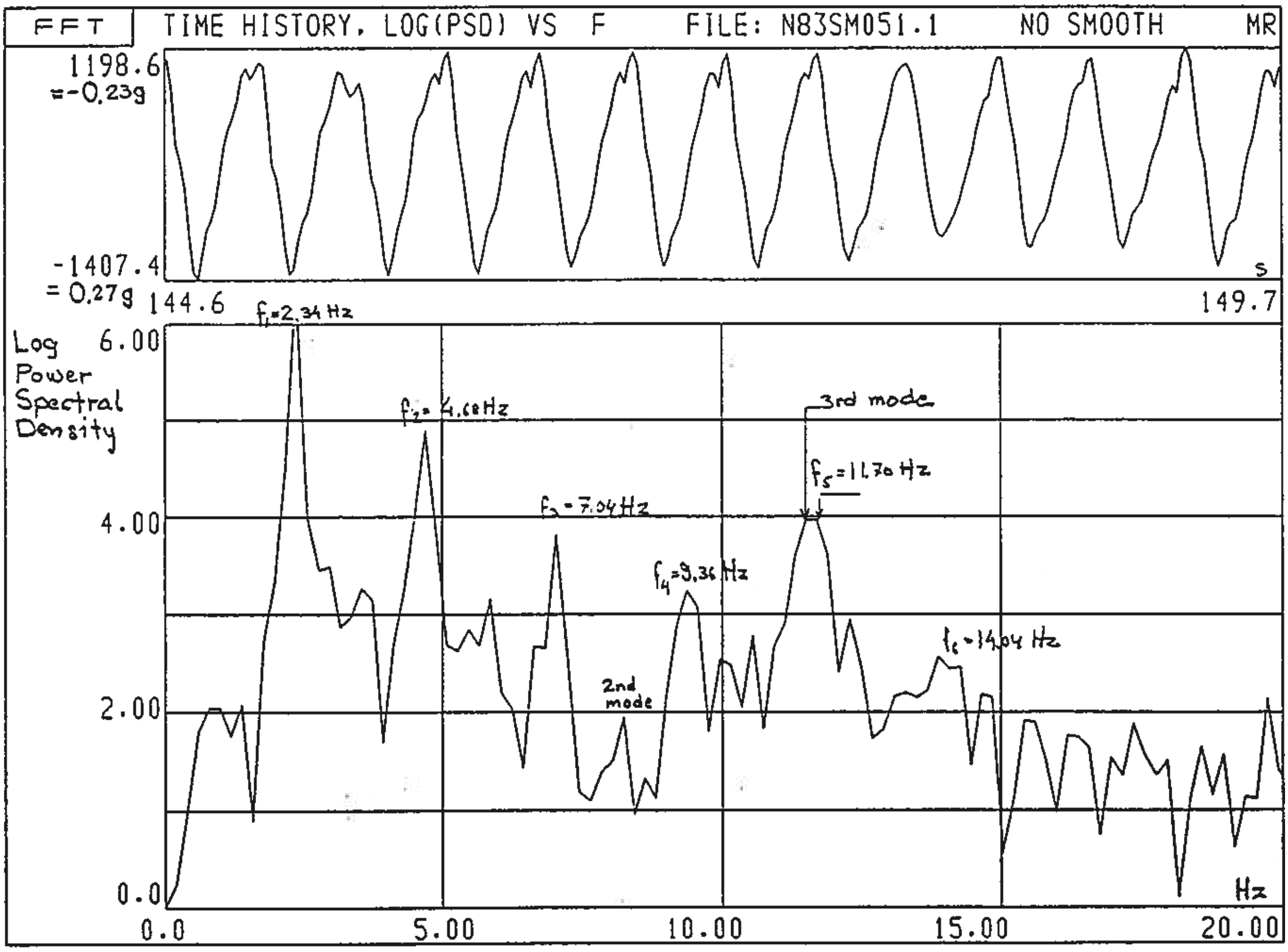

Figure 6:4

(2) Filtered acceleration signals

As illustrated in the logaritmic Power Density Spectrum (Figure 6:4), the vibration amplitudes are very much concentrated around the peaks representing the fundamental frequency and its multiples. Since the aim of the study is to define a generalized ice force time-history for resonance vibrations, the very small vibrations within the intermediate frequency ranges can be neglected which is also a condition for the validity of the transformation model.

Therefore, the first step of the signal processing is to filter the signals as illustrated in Figure 6:5. This can be done without any significant loss of vibration energy and it results in a "smoothed" accelerogram, composed of essentially sinusoidal components with frequencies corresponding to the fundamental eigenfrequency and its multiples (n = 1-6).

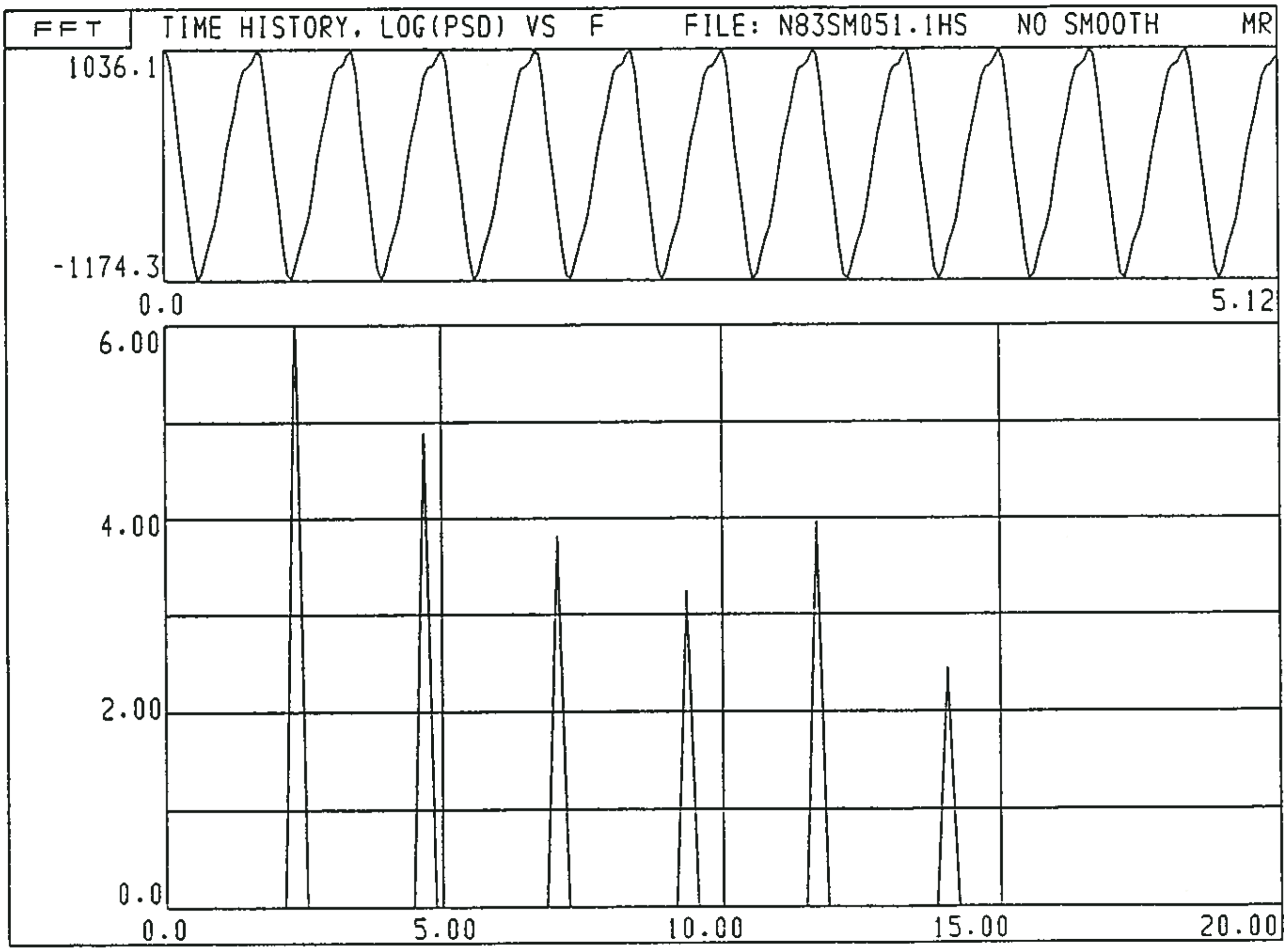

Figure 6:5

(3) Disintegration of the acceleration signals

The various components of the filtered signal shown in Figure 6:5 are displayed together with their Power Density Spectra in Figures 6:6 and 6:7. The lower frequency signals are very regular and sinusoidal, whereas the higher frequency signals are slightly irregular, depending partly on the limited resolution of the measurement frequency (50 Hz), However, without any significant loss of accuracy the various components can be treated as sine components in the transformation process:

$$\ddot{x}_n = \ddot{x}_{n\,max} \cdot \sin(\omega_n t + \phi_n)$$

The amplitudes $\ddot{x}_{n\,max}$ are given in "signal units" which are to be multiplied by -0.00191 (for Signal 1) to obtain the acceleration value in m/s^2 (+0.00191 for Signal 2).

The amplitudes and phase angles are as follows:

n	ϕ_n (rad.)	$\ddot{x}_{n\,max}$ (m/s^2)
1	2.0647	-1.960
2	0.6283	-0.3316
3	5.7002	-0.0966
4	1.2566	-0.0491
5	0	-0.1150
6	0.4485	-0.0199

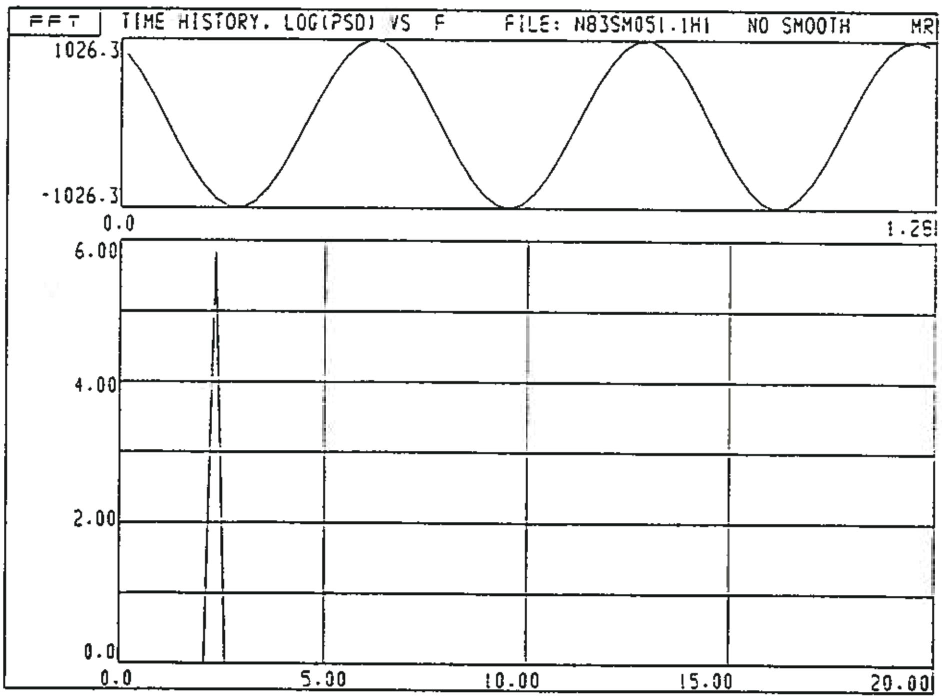

Figure 6:6

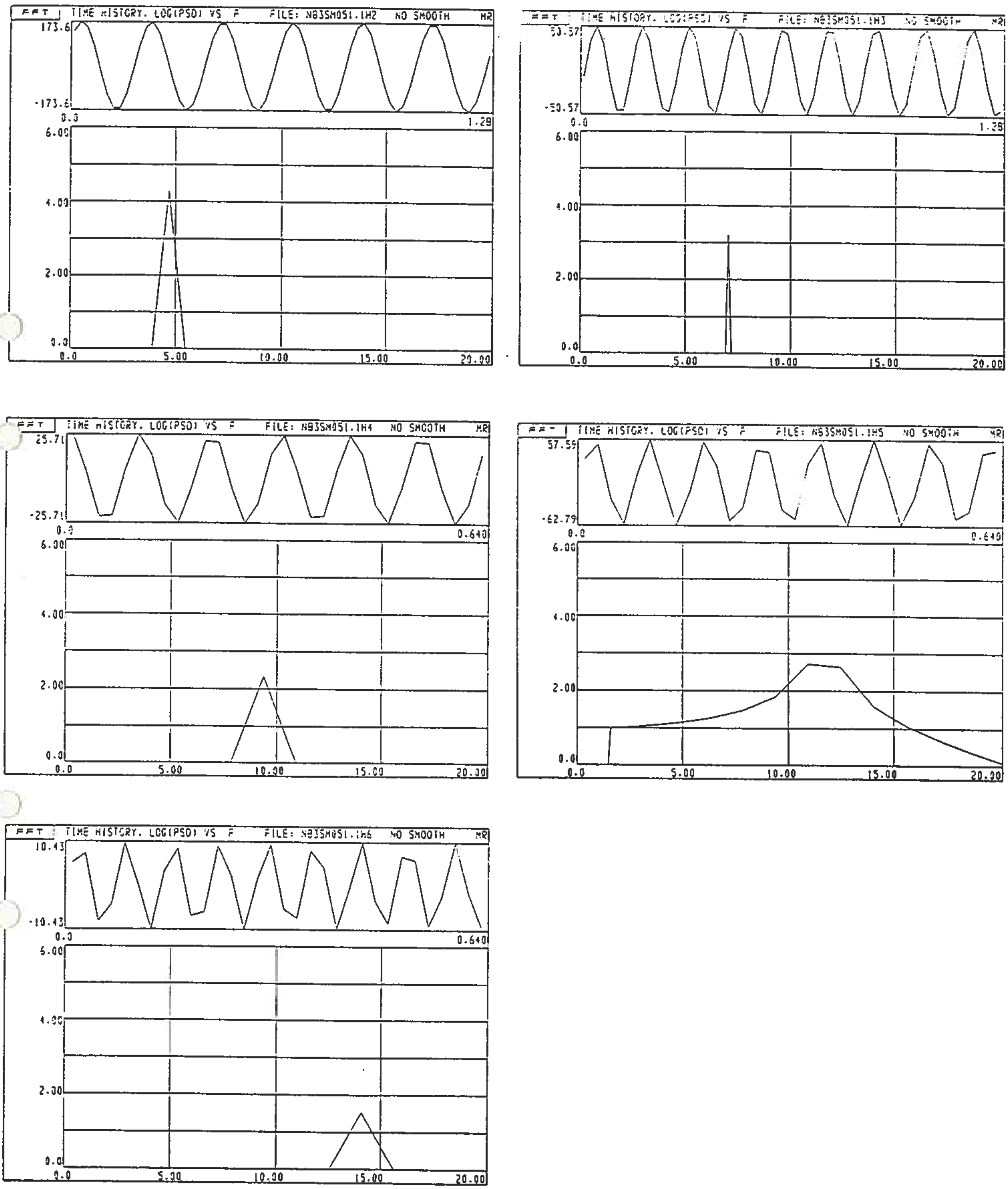
FFT TIME HISTORY. LOG(PSD) VS F FILE: N83SM051.1H2 NO SMOOTH HR
173.6
-173.6
0.0
1.28
6.00
4.00
2.00
0.0
5.00
10.00
15.00
20.00
FFT TIME HISTORY. LOG(PSD) VS F FILE: N83SM051.1H3 NO SMOOTH HR
50.57
-50.57
1.28
FFT TIME HISTORY. LOG(PSD) VS F FILE: N83SM051.1H4 NO SMOOTH HR
25.71
-25.71
0.640
FFT TIME HISTORY. LOG(PSD) VS F FILE: N83SM051.1H5 NO SMOOTH HR
57.59
-62.79
FFT TIME HISTORY. LOG(PSD) VS F FILE: N83SM051.1H6 NO SMOOTH HR
10.43
-10.43

Figure 6:7

(4) **Transformation of acceleration signals to ice force components**

The ice force components

$$F_n = F_{n\,max} \cdot \sin(n\omega_1 t + \Theta_n)$$

are obtained from the acceleration functions derived under point (3) and the unit force response relations dealt with in Subsection 6.2.2 which give the following expressions for the amplitude and phase angle of each ice force component

$$\Theta_n = \phi_n - \varphi_n$$

$$F_{n\,max} = -\ddot{x}_{n\,max}/a_{n\,max}$$

The resulting ice force components for n = 1-3 are displayed in Figure 6:8

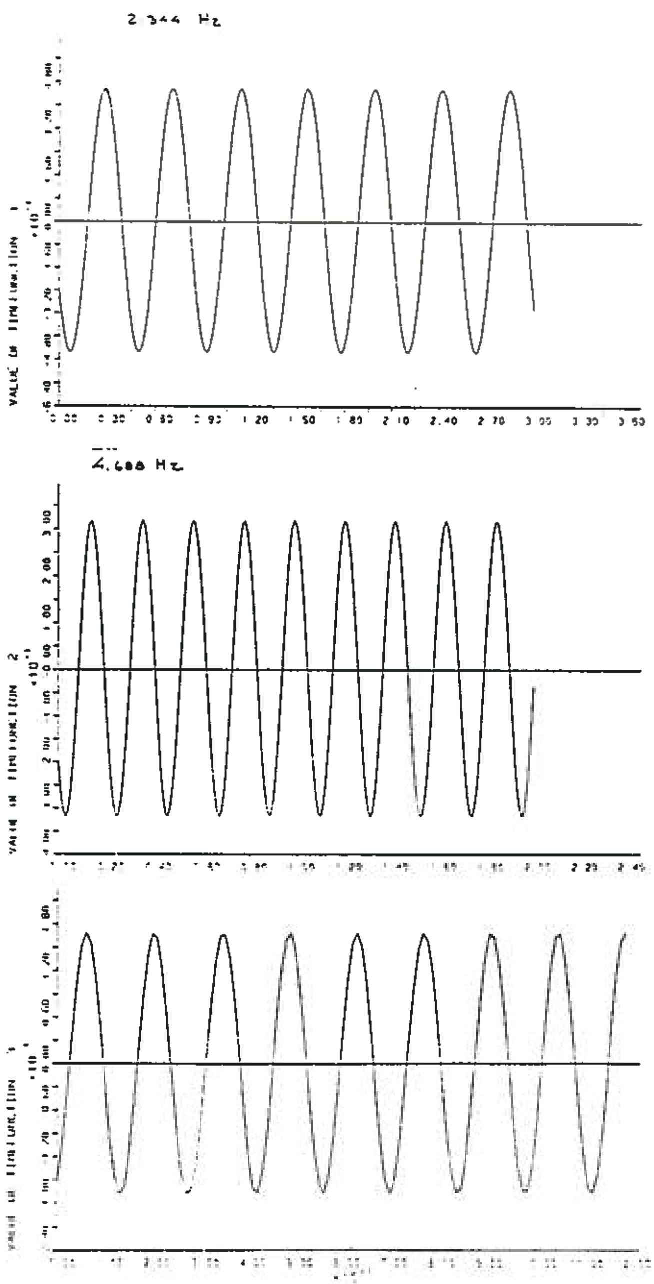

Figure 6:8

(5) Superposition of ice force sine components in Direction 1

The amplitudes and phase angles obtained by transformation of acceleration signals are as follows:

n	$F_{n\,max}$ (MN)	θ_n (rad.)
1	-0.456	0.553
2	-0.319	0.650
3	-0.169	2.382
4	(-0.10)	4.266
5	(-0.10)	2.864

Negative amplitudes only indicate the direction of the ice force in the selected coordinate system. The sign is neglected in the graphs below. The amplitudes of the components 4-6 could only be roughly estimated due to a considerable uncertainty as regards the shape of the 3rd mode of vibration near to the measurement level.

The resulting sums of the ice force components n = 1-3 and n = 1-5, respectively, are displayed in Figure 6:9. It appears, that the contributions of the 4th and 5th components still tend to be affected by a considerable uncertainty. At present, it is preferred only to rely on the components n = 1-3 to represent the "dynamic" part of the ice force time-history.

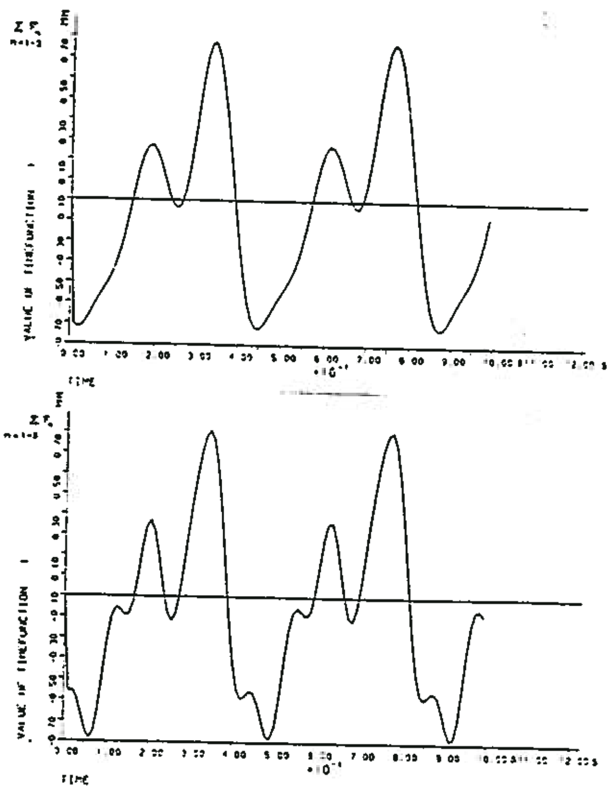

Figure 6:9

(6) Superposition of static and dynamic as well as directional components

The "dynamic" ice force time history in Direction 1 is to be added to the "low-frequency" or "static" ice force component, determined by inclinometer measurements as described in Section 4.

$$F(t) = F_o(t) + \Sigma F_{n\,max} \cdot \sin(n\omega_1 t + \theta_n)$$

For the sequence studied the "static" ice force was almost constant: $F_o = 1.98$ MN.

Finally, the time-history of the resultant global ice force can be obtained by vector summation of the directional components at discrete points of time. Thus, the resultant of the components along Direction 1 and 2 for the selected sequence has been computed. The time-history is displayed in Figure 6:10. However, since the direction of the resultant varies, the unidirectional components along Direction 1 and 2 are preferred as a basis for generalization of ice load components.

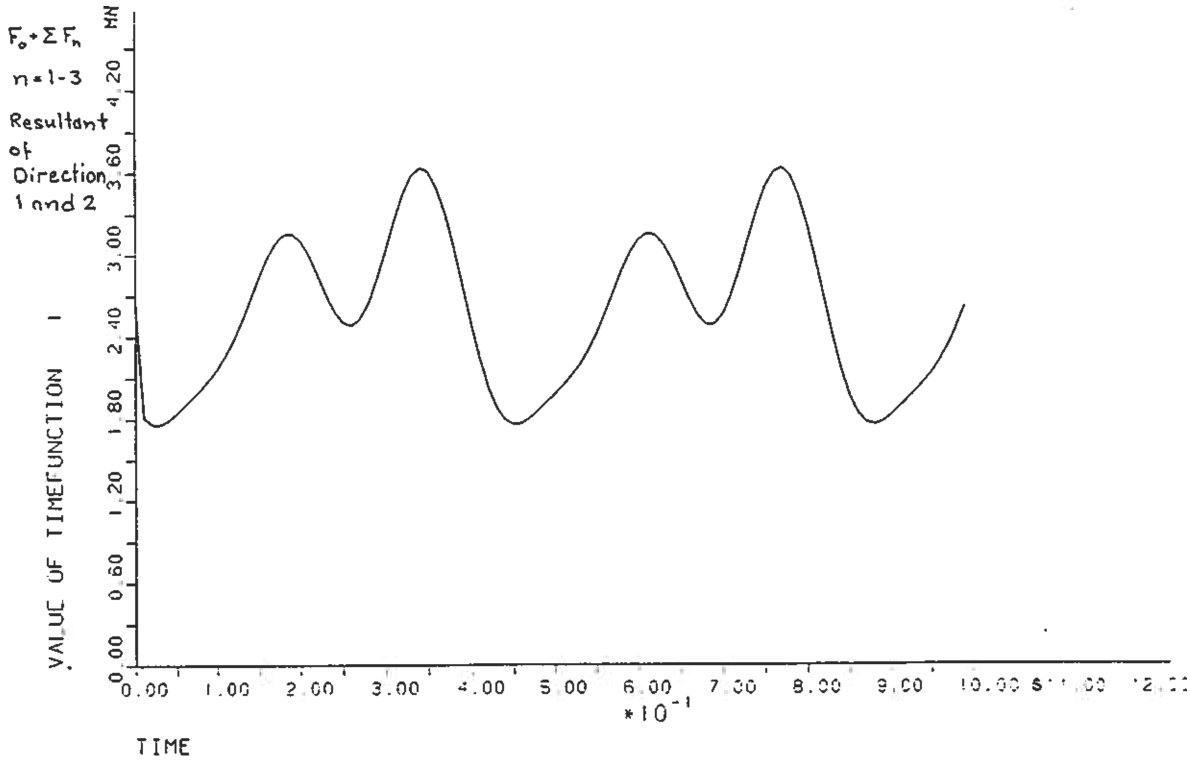

Figure 6:10