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USE OF FORCED RESPONSE MEASUREMENTS FOR THE ESTIMATION OF MACHINE SOURCE PROPERTIES

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INTRODUCTION

In an earlier paper, Kinns [1] described a procedure for estimating fluctuating bearing forces in rotating machines at multiples of shaft rotational frequency. The method involved the application of the Reciprocity Theorem and the use of a multiple regression procedure. In this paper, the method is applied to the case of a marine turbo-alternator along with some extensions which use standard statistical techniques to determine the degree of self-consistency exhibited by the elements of the data set.

THE FORCE ESTIMATION PROCEDURE

Suppose that precisely m machine forces ($F_1, F_2, \ldots, F_m$) act at the frequency of interest (f Hz), and that vibration is measured at n (>m) positions on the structure. The acceleration response measured at the ith position due to the jth force is

$\alpha_{ij} = H_{ij}F_j$

where H_{ij} is the (complex) transfer function value. The total acceleration measured at position i is the sum of components due to each force plus a random error term, viz

$$A_i = \sum_{j=1}^{m} H_{ij}F_j + \epsilon_i .$$

These n equations can be written in the equivalent matrix form

$$\underset{\sim}{A} = H\underset{\sim}{F} + \underset{\sim}{\epsilon} \qquad (1)$$

where $\underset{\sim}{A} = \left[A_i\right]_{n\times1}$, $H = \left[H_{ij}\right]_{n\times m}$, $\underset{\sim}{F} = \left[F_j\right]_{m\times1}$, $\underset{\sim}{\epsilon} = \left[\epsilon_i\right]_{n\times1}$

By the Reciprocity Theorem, each H_{ij} can be determined by applying tonal excitation at f Hz through an electro-magnetic shaker mounted at the ith structural location and measuring response at the point of action of the jth force. If measurement errors here are negligible, then estimating F from (1) is analogous to a Multiple Regression problem and, by a complex analogue of Ordinary Least Squares, an estimator, $\hat{F}$, of F can be found by minimising the sum of the squared magnitudes of residuals

$$|\underset{\sim}{A} - H\underset{\sim}{F}|^2 = \Sigma|A_i - \Sigma H_{ij}F_j|^2$$

TESTS ON MARINE TURBO-ALTERNATORS

Measurements were made on two marine turbo-alternators of the same type, to determine their dynamic transmission properties both when stopped and when running normally. Checks on reciprocal behaviour were carried out, and the structures were found to exhibit good reciprocity. An example is shown in Figure 1. The presence of higher background noise levels at one of the positions of acceleration measurement accounts for much of the apparent divergence between the two transfer functions at high frequencies. There was close agreement between the dynamic properties of the two sets when running. However, when the sets were stopped, substantial differences between them were found. It was found that the loss factor of each set was different when running from that observed when the set was stopped. This can be seen very clearly from the results of Figure 2. It is believed this difference in loss factor is due to the behaviour of the bearing oil films.

For the purpose of estimating bearing forces, two different sets of measurements were carried out, on one of the two turbo-alternators, with an interval of eighteen months between them. It was expected that there would be nine forces operating at the bearings (one force in each of three orthogonal directions at each of three bearings), and a total of twelve positions of shaker input (S1 - S12) were used to provide for some degree of redundancy in the regression.

Table 1 shows the results obtained from regressions on the two sets of measurements. Also shown is the estimated standard deviation of the resulting force estimates. There are obvious differences between the two sets of force estimates, both in magnitude and relative phase. However, examination of the standard deviations indicate that there are greater uncertainties associated with the later of the two sets of trials data. By inspection, it was suggested that the vibration measurements obtained during the second trial were in error. This was later confirmed by statistical tests which indicated that data for S11 were responsible for reducing the confidence in the force estimates produced.

Elimination of the suspect data, led to the set of force estimates shown in Table 2. The standard deviations are now similar to those obtained during the earlier of the two sets of trials, indicating a high degree of self-consistency for both sets of results. A formal statistical test was carried out to test the hypothesis that the detailed distribution of machine forces had remained unaltered in the interval between the two sets of trials. The results indicated that such a hypothesis must be rejected. It is concluded, therefore, that the detailed distribution of bearing forces within the machine had changed through time though the overall level of forces at each bearing had remained similar.

CONCLUSION

It has been shown that estimates of fluctuating bearing forces in rotating machines can be obtained from the technique described. By the use of standard statistical tests, the quality of the data used in the estimation can be checked for self-consistency and poor data eliminated.

Application of the technique to the case of a marine turbo-alternator indicates that, after discarding inconsistent vibration data, force estimates of high self-consistency can be obtained. Examination of two sets of such estimates for the same machine, but from measurements made eighteen months apart, shows that the distribution of forces within the set had altered within that time.

ACKNOWLEDGMENT

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REFERENCE

1 R. Kinns, "The deduction of bearing forces in rotating machinery" (in J.L. Armand, R.E.D. Bishop (Eds) "Numerical analysis of the dynamics of ship structures: Proceedings of EUROMECH Colloquium 122", ATMA, 1979, pp 345-361).

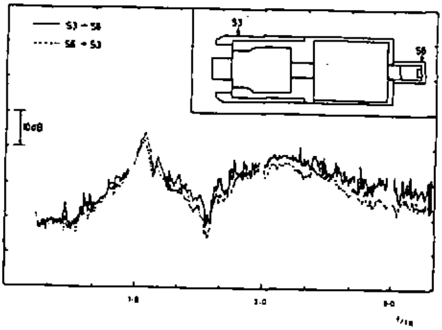
Table 1. Initial Bearing Force Estimates (dB ref rotor weight)

	Dec. 1978 Transfer Function Dec. 1978 Acceleration Data			Dec. 1978 Transfer Function Sept. 1980 Acceleration Data			Sept. 1980 Transfer Function Dec. 1978 Acceleration Data			Sept. 1980 Transfer Function Sept. 1980 Acceleration Data		
Location	Mag.	Phase	Est. Norm. Standard Deviation	Mag.	Phase	Est. Norm. Standard Deviation	Mag.	Phase	Est. Norm. Standard Deviation	Mag.	Phase	Est. Norm. Standard Deviation
Fwd. Turbine Bearing												
Vertical	[illegible]	0	[illegible]	[illegible]	0	[illegible]	[illegible]	0	[illegible]	[illegible]	0	10.3
Axial	[illegible]	[illegible]	1.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-103	3.7
Transverse	[illegible]	[illegible]	0.40	[illegible]	-141	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-5	[illegible]
Fwd. Alternator Bearing												
Vertical	[illegible]	[illegible]	[illegible]	-33	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-131	[illegible]
Axial	[illegible]	[illegible]	[illegible]	[illegible]	-115	[illegible]	[illegible]	[illegible]	1.07	[illegible]	-67	[illegible]
Transverse	-37	[illegible]	0.37	[illegible]	-171	[illegible]	-37	+133	[illegible]	[illegible]	[illegible]	[illegible]
Aft. Alternator Bearing												
Vertical	[illegible]	[illegible]	0.23	[illegible]	[illegible]	1.17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.4
Axial	[illegible]	-142	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-13	0.15	[illegible]	[illegible]	[illegible]
Transverse	-35	[illegible]	0.19	-32	-173	[illegible]	[illegible]	-143	0.10	[illegible]	-75	[illegible]

Table 2. Revised Bearing Force Estimates (dB ref rotor weight)

Location	September 1980 Results Before Elimination of Support Vibration Data			September 1980 Results After Elimination of Support Vibration Data		
	Mag.	Phase	Estimated Norm. Stan. Dev.	Mag.	Phase	Estimated Norm. Stan. Dev.
Fwd. Turbine Bearing						
Vertical	-36	0	10.3	-40	3	0.3[illegible]
Axial	-42	-103	3.7	-4[illegible]	+ 5[illegible]	0.6[illegible]
Transverse	-4[illegible]	- 8	3.6	-42	- 82	2.4[illegible]
Fwd. Alternator Bearing						
Vertical	-25	-131	1.2	-33	- 14	0.36
Axial	-30	- 67	1.8	-49	-132	3.20
Transverse	-23	- 64	0.6	-49	+105	[illegible]
Aft. Alternator Bearing						
Vertical	-35	- 98	1.4	-35	- 11	0.20
Axial	-38	- 46	0.7	-41	- 11	0.19
Transverse	-30	- 75	0.6	-38	-118	0.33

Figure 1.
Reciprocity Check on Turbo-Alternator



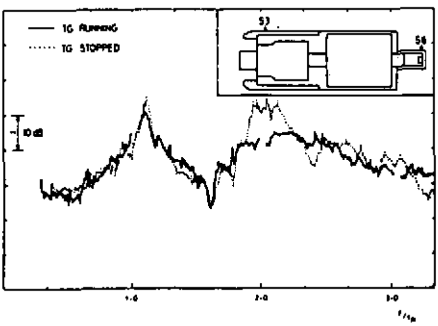


Figure 2.
Comparison of Turbo-Alternator Behaviour When Stopped and Running