BALANCING TURBO MACHINERY ON BOARD OR ASHORE

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Then at the balance let's be mute,
We never can adjust it

Burns

Introduction

In spite of Burns we can adjust machinery balance and this adjustment is particularly important in submarines in reducing radiated noise. This paper describes how the Noise and Vibration Engineering Department (NAVED) of Vickers Shipbuilding and Engineering Ltd (VSEL) has extended the standard methods to achieve a much finer quality of balance in the largest submarine machines, the turbo generators (TGs) and main turbines. It also covers progress on introducing the new method into the Fleet as a routine operation.

STANDARD METHODS OF BALANCE

The improved method can best be appreciated by first reviewing the standard methods of reaching a good balance, which are generally aimed at machinery health.

Single Plane Balancing

The simplest method is to balance at one plane only, using an accelerometer and a means of relating the phase of the accelerometer to a datum on the shaft, as illustrated in Fig. 1. Here the shaft has been painted half black and half white so that the signal from an infra-red probe looking at the shaft is a square wave, which can then be used to give the phase datum.

The basic data are acquired as follows:

(*a*) Run the machine and measure the vibration level (A) on the accelerometer and its phase angle (θ) at the rotational frequency and relative to the datum.

(*b*) Stop the machine and add a trial weight at any position.

(*c*) Run the machine and measure the new vibrational level (B) at the new phase angle (ϕ).

The machine can then be balanced in the following manner (see Fig. 2):

(*a*) Plot vector OA at angle θ

(*b*) Plot vector OB at angle ϕ

(*c*) Complete the parallelogram of forces

This shows that the new state of unbalance OB is the resultant of the original unbalance OA and the unbalance caused by the trial weight OC.

Now the vector due to OC must lie on the trial weight radius (see Fig. 3). This vector OC is termed an influence vector and scaling it by the mass of the trial weight gives the influence coefficient, to be referred to later.

The position of the balance weight required to correct the original unbalance is shown at the angle X° to the trial weight position. Its magnitude can be calculated by relating the centrifugal forces due to the balance weight and the original unbalance i.e. $\frac{OA}{OC}$. The magnitude of the balance weight is therefore

$$\text{Balance weight} = \text{trial weight} \times \frac{OA}{OC}$$

and must be placed at angle X° from the trial weight (which is of course removed).

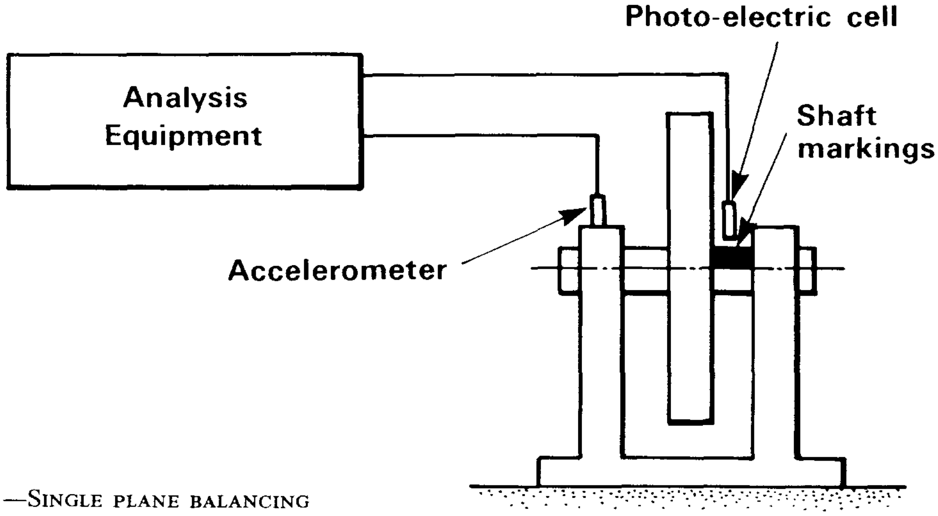

Fig. 1—Single plane balancing

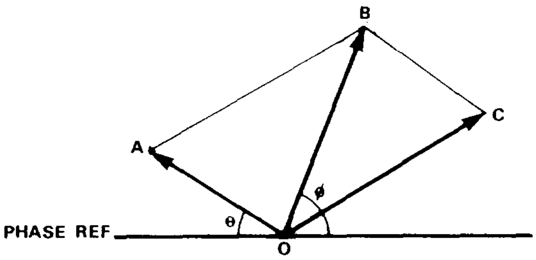

FIG. 2—SINGLE PLANE BALANCING: VECTORS

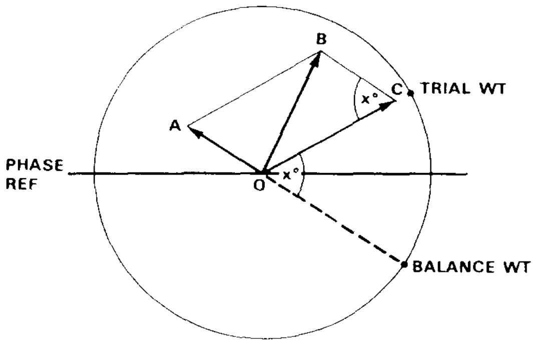

FIG. 3—SINGLE PLANE BALANCING: VECTORS AND WEIGHTS

The same result can be obtained by the Sommervaille method using only the accelerometer with no phase measurements. In this case the machine must be run four times, the original unbalance run and three runs with the trial weight in different positions. The vector diagram can then be drawn geometrically. The equipment required is simpler (one accelerometer only) but the time taken is longer.

Two Plane Balancing

In most practical cases a single plane balance will not produce the best results because the rotating mass is not in one plane but distributed axially. This means that although static balance can be achieved by balance weight adjustments in one plane only, in general this will not give a dynamic balance.

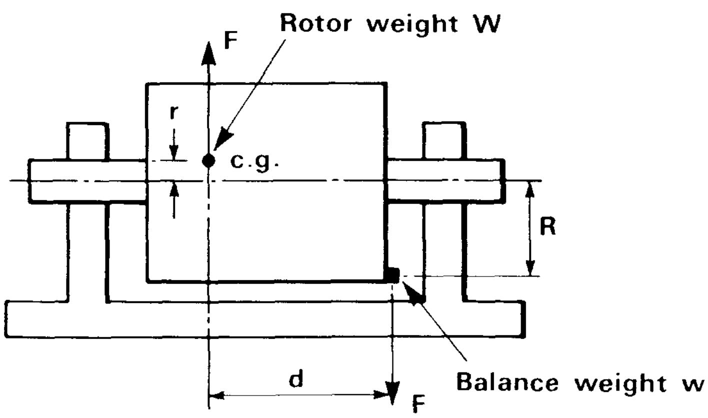

FIG. 4—ROTOR BALANCED STATICALLY BUT NOT DYNAMICALLY

A rotor which has its centre of gravity offset from the rotational axis is both statically and dynamically out of balance. Adding the balance weight (w) whose moment about the axis exactly balances the rotor out of balance (W) gives static balance ($Wr = wR$) but leaves a dynamic unbalance couple of magnitude $F \times d$ (FIG. 4). This couple must also be eliminated, which can be achieved by adding balance weights at each end of the rotor, of total mass equal to that of the single balance weight. Thus in FIG. 5 $Wr = (w_1 + w_2)R$ and also $F_1d_1 = F_2d_2$.

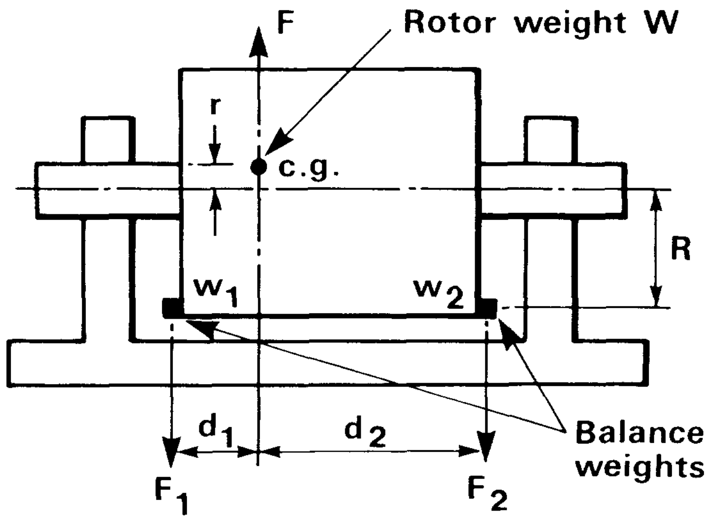

FIG. 5—ROTOR BALANCED STATICALLY AND DYNAMICALLY

Fortunately the influence coefficient system can easily be extended to two or more parallel planes and so the procedure for two plane balancing is a development of the single plane method. The equipment used is shown in FIG. 6. There is an accelerometer at both bearing caps, a photo-electric cell for the phase datum, a means of adding balance weights at each end of the rotor, and the necessary signal processing equipment. The machine is run as received and the accelerometer and phase measurements are taken from each transducer. A trial weight is then added at one end and the measurement repeated. The trial weight is then transferred to the other end and again the measurement is taken.

The solution is calculated using a matrix vectorization routine which is sufficiently complicated for a programmable calculator to be generally used. As there are two measurement points and two balance planes, it is possible, in theory, to obtain a solution for the balance weights required which will reduce the measured vibrations to zero.

The method gives good results but is very dependent on the quality of the measured data and, in particular, significant changes in amplitude and/or phase have to be obtained with each trial weight for success.

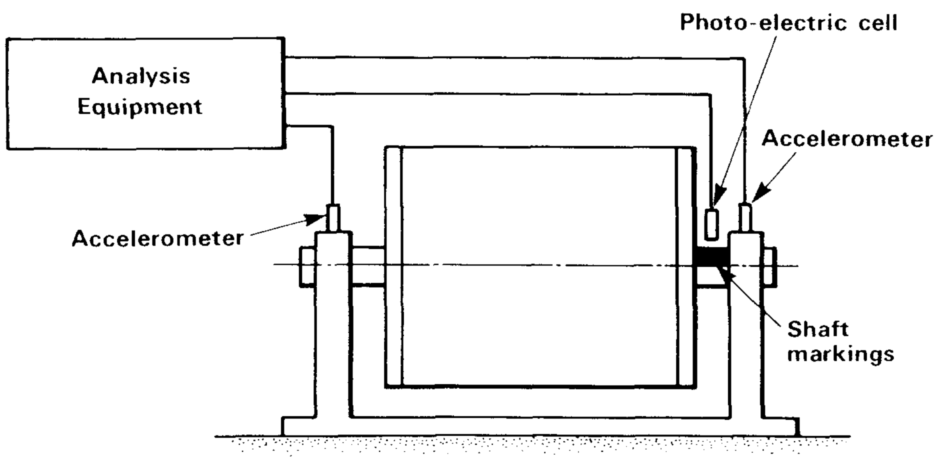

FIG. 6—TWO PLANE BALANCING

IMPROVEMENTS TO THE STANDARD METHOD

'Least Squares' Solution

The standard method can be improved if the number of measurements is increased. In this case there can be no direct solution as there are more variables (measurements) to be reduced to zero than there are equations (balance planes) to solve. However a unique solution can be obtained if the further condition is applied that the length of the residual vector is minimized. This is called the Least Squares solution and in physical terms can be thought of as minimizing the total residual vibration energy at the measurement points.

The method has the following advantages:

(*a*) Vertical and horizontal measurements take fuller account of the rotor and its bearings.

(*b*) Above mount vibration levels can be included, which is important as the mounts are the most likely transmission path for radiated noise.

(*c*) The effects of an error in any reading are reduced.

This approach has been available in a research form for some time. The NAVED contribution is to devise a package of hardware and software which can be used for balancing on board. The solution requires the use of a microcomputer.

Multi-plane Balancing

The balance of a machine can be further improved by increasing the number of balance planes. For most rotating machinery, two plane balancing or even single plane balancing has been found to be adequate but using the many planes available on turbo-generators and main propulsion machinery has produced much better results.

The approach is similar to two plane balancing with trial weights added at each of the balance planes in turn. The matrices to be solved are obviously larger and again the Least Squares method is used. The NAVED computer programme is capable, in its present form, of dealing with ten balance planes and twenty measurements.

Choice of measurements

Measurements could be made at any point on or around the machine, in any direction, for the Least Squares method. At the outset, the measurements which seemed likely to give the best balancing results were:

(*a*) Bearing caps—being the nearest accessible place to the source of vibration and therefore the most sensitive with the highest amplitude.

(*b*) Above mounts—being on the transmission path and still of high amplitude.

(*c*) Hull—being again on the main transmission path and more nearly related to noise in the water.

(*d*) In water (using hydrophones)—since the reduction of radiated noise is the ultimate aim.

All were tried but some were found to be insufficiently sensitive. Also some of the bearing cap readings were too sensitive, especially those on small overhung components such as the diode carrier of the TRAFALGAR Class turbo-generators. In this case the mobility of the item gave high acceleration readings but was not an important contributor to the vibration energy transmitted from the whole machine.

Turbo-Generator Balancing

The complexity of the method varies because the SSBN and VALIANT Classes have only two accessible balance planes (at each end of the alternator); later classes have more. The measurement positions used are given in TABLE I.

TABLE I—*Measurement Positions for Turbo-Generator Balancing*

	Bearing Caps		*Above Mounts*		*Total number of measurements*
	direction	*number*	*direction*	*number*	
SSBN	Vertical and Transverse	4	Vertical	6	10
VALIANT	Vertical and Transverse	4	Vertical	6	10
SWIFTSURE	Vertical and Transverse	8	Vertical	4	12
TRAFALGAR	Vertical and Transverse	10	Vertical	8	18

Measurements were also attempted on the forward end of the turbine in the SSBN and VALIANT Classes but the position was too hot for the transducers.

The time taken to collect the data for balancing two TGs is considerable as at least N + 1 runs are required (where N is the number of balance planes) for each machine. Between each run a weight change is required. After the results are computed, balance weights must be placed in the correct positions on each plane and a final run carried out to confirm the balance has been achieved.

The time can be reduced by balancing both TGs simultaneously using the following procedure:

(*a*) With both sets running, split the TG frequencies to port 60 Hz, starboard 58.5 Hz, these being nearly the same but sufficiently distinct to be identified.

(*b*) Take the initial readings on the port TG at about 500 kW load.

(*c*) Stop the port TG and carry out the first weight change.

(*d*) Set the starboard TG at 60 Hz and load it to 500 kW.

(*e*) Take the initial readings on the starboard TG.

(*f*) Run up the port TG and load it; stop the starboard TG.

(*g*) Carry out a weight change on the starboard TG and meantime take the first trial weight readings in the port TG.

(*h*) Run up the starboard TG to load; stop the port TG.

(*j*) Carry out the next weight change on the port TG while taking the first trial weight readings on the starboard TG.

(*k*) Continue the procedure until all the data is collected.

Main Machinery Balancing

Balancing main machinery has so far only been achieved in full on the TRAFALGAR Class machinery in SMITE, the shore test facility at VSEL.

A number of balance planes are available in the TRAFALGAR Class, and the Least Squares method is further extended to include balancing at two speeds.

The SMITE balancing was done under load but this is very difficult once the machinery has been installed in a submarine as it would require long periods at sea running at speed, alternating with periods when the main turbines were shut down to alter trial weights. The first SWIFTSURE Class boats to be refitted were therefore balanced with each turbine declutched in turn. A further trial will be carried out at SMITE to see if a better balance can be obtained by disconnecting the main coupling and balancing both turbines and gearbox under no load conditions. Trials on the machinery at SMITE have shown that this is mechanically possible, with vibration levels being steady enough to take reliable readings for balancing.

Improvements

It is unfortunately not possible to compare the *in situ* balance results with the criteria normally laid down in R.N. references. GMES, for instance, sets a standard of 4 W/N ounce-inches (where W is in pounds and N in r.p.m.) for a free rotor, but this torque standard cannot be translated into vibration terms (e.g. Acceleration dB or absolute velocity (mm/sec), etc.) without knowledge of the supporting structure of the turbine bearings. BR 4010(5B) for SWIFTSURE Class submarines does however complement the stricter criterion of 1·35 W/N by a requirement to achieve 0·2 in/sec RMS at the bearing caps on board. The latter level is equivalent to 106 AdB (by a purely mathematical conversion) at 60 Hz. The NAVED achievement is very considerably better than this.

Implementation

The method is now considered to be proven but must now be turned from the development stage into a routine maintenance operation. The present intention is to check and, if necessary, repeat the balance annually for TGs. This one year cycle is arbitrary so far, as there is little experience of how long so fine a balance will last. Repeat measurements have so far shown no significant deterioration after six months. Main machinery will only be balanced in build and after refit.

The number of balancing teams required for this work load will depend on:

(*a*) being able to cope with the number of balances, while

(*b*) carrying out enough balances each year to ensure expertise is maintained.

CED have indicated that they do not wish to set up Dockyard teams, who would necessarily have to try and fit the lengthy balancing procedure into the last few crowded weeks of a refit when the boat has steam available. Instead, it is intended that two naval teams will be trained, based on the present Fleet Vibration Analysis teams, and located at Devonport and Faslane. In addition the NAVED teams will be available to cover emergencies and routine balances during build.

Equipment

The equipment needed for the task is still being selected. The naval teams would prefer to continue with the equipment they already use for vibration analysis for health monitoring and there are also obvious logistic advantages with this approach. NAVED however consider there are serious shortcomings with this equipment when dealing with the large numbers of measurements required for the multi-plane least squares method and recommend more sophisticated equipment. A dialogue has been initiated between NAVED and the Vibration Analysis Teams.

Whichever equipment is chosen, NAVED will rewrite their current computer programme to be more 'user friendly' and to be compatible with whichever computer is finally selected.

Training

Because the technique requires a higher degree of sophistication than most vibration analysis, the R.N. personnel must be of high calibre and training is going to be an important task. NAVED will supply the initial training with a course combining theory and 'hands on' experience of the method. This will be followed by balancing at SMITE or on board with NAVED first carrying out balances with the naval teams observing and later being on hand while the naval teams perform the balance. Once the first team is trained, however, it is expected that new members will be taught on the job. This in turn will require careful control of postings to ensure continuity.

Modifications to Turbo-Generators

Some modifications to the TGs have been proposed which would greatly help the process.

(*a*) Access to the balance planes has been improved in the SWIFTSURE Class alternator.

(*b*) Action is underway to improve the method of adding balance weights by periodic rationalizing of the weights already added to the planes.

(*c*) In parallel, attempts are being made to get each balance plane marked with phase angles in a permanent position.

Conclusion

NAVED have developed a research method of balancing into one suitable for use on board and by this means have reduced machinery vibration and radiated noise levels by substantial amounts.

The method is now being converted into a routine maintenance operation and the necessary logistic, training, and modification work is well under way.