DISCUSSION

Frank J. Heymann[2]

The author has given a clear and interesting description of how the balancing of rotating machinery is a combination of an empirical phase (obtaining response coefficients from the results of trial balance moves) and an analytic phase (chosing some linear combination of the trial moves so as to optimize the predicted results of such a combination balance move), and of how this analytic phase was approached and programmed for a digital computer.

The writer's company also is involved in the fine balancing of marine propulsion equipment, and has developed a computer program whose basic approach is identical to that described by Professor Goodman. There are some points of difference, however, whose enumeration may be of interest.

Our method is based on a modified least-squares optimizing objective, and is not designed to seek a "mini-max" solution as does Professor Goodman's. It was felt that, in an application where vibrations are invariably within mechanically acceptable limits and the main objective of finer balance is noise reduction, a minimizing of the sum of squares is an appropriate objective. That is perhaps open to discussion, and in any case Professor Goodman's program gives the engineer the choice of using the plain least squares or the mini-max solution; this is a valuable and powerful feature of his approach.

Our modification to the plain least-squares approach was stimulated by the following observation: In practice, plain least-squares solutions sometimes prescribe rather large balance corrections which essentially buck each other; in other words, at any particular pickup location, the effect due to each balance plane correction by itself may be large compared to the combined effect and compared to the predicted residual amplitude. This is undesirable for two reasons: First, the magnitude of the prescribed balance corrections may be impracticably large; and second, the response coefficients obtained from trial data are not always accurately reproducible and their errors, when multiplied by large balance corrections, can in such cases reduce or completely swamp out the net reduction predicted in the residual amplitude.

The stratagem which we have used to avoid such solutions is to associate with each response coefficient an uncertainty expressed as a statistical variance, and to adopt an optimization objective which minimizes the sum of squares of the (predicted) residual amplitudes *plus* the sum of the variances of these amplitudes, resulting from the response coefficient variances. It can be seen qualitatively that this will inhibit solutions with large mass corrections in general, and particularly in balance planes for which response coefficients may have been specified as less "reliable" than for other planes. Mathematically, only minor modifications are required in the equations to be solved, and with certain postulates this approach can be shown to give the rigorously correct least-squares solution on a statistical basis. It should be pointed out that in this type of solution (as in the mini-max solution) the sum of squares of the residual amplitudes will necessarily be larger than that predicted in the plain least squares solution.

The quantity to be minimized is further modified by a number of arbitrary weighting coefficients by which the relative importance of various pickup locations and operating speeds or conditions can be adjusted; presumably the program Professor Goodman describes has similar provisions which, for simplicity, were not mentioned in the paper.

A second major accommodation to practical desires reflects the reluctance of balancing engineers to employ all of the balance planes in any one move. Accordingly, our program can (if so instructed) first compute a solution in which all balance planes are used, determine which balance plane contributed least to the net reduction in the quantity to be minimized, and then compute a second solution in which that plane is omitted. This procedure can be repeated until the number of planes considered is reduced to one. The engineer then has the choice as to which of these several solutions provides the best compromise between balancing effectiveness and implementation ease. The procedure used does not rigorously guarantee that, when the number of planes has been reduced to, say, N, those remaining in consideration can provide the best possible N-plane move, but test cases have indicated that generally they do.

Another optional convenience which we have built into our program is the ability to translate the prescribed balance correction in each plane, from simply a vector description, into actual instructions in terms of balance plug hole numbers and balance plug weights to be removed or added. This option requires that the program input include appropriate data on the number of holes, their angular positions, the maximum and minimum weights of balance plugs, and the locations and weights of plugs currently installed. The instructions generated cannot be unique and are not necessarily the simplest possible (resulting as they do from a specific programmed ritual), but can save a good deal of hand calculation when much vectoring is required.

My final remarks pertain to the problems met with in establishing the use of such a program for production-line balancing:

1 It requires a reorientation and a change of approach and scheduling on the part of balancing engineers. In "hand" balancing, trial move data are generally obtained for only a few balance planes believed to be useful, and "bad" runs are often halted before data are obtained at all conditions. The objective is to get enough data for more-or-less subjective projections as quickly as possible. In order to use the computer approach to its best advantage, a systematic procedure is necessary in which complete trial data are obtained for all balance planes at all speeds or conditions.

2 Since a shop operation is involved, the program input should be simple and quick. In our case, this was made difficult by the fact that in order to least disturb the established balancing procedures, all conceivable flexibilities were built into the program, particularly as regards the form and units in which trial move data are entered. This aim has been somewhat self-defeating, in that the input is cumbersome and difficult to master, and tends to discourage use of the program.

3 Ready access to the computer and quick turn-around time is essential. Here again we suffer from the complexity of the program, which requires the memory capacity of our central engineering computer, an IBM-7094. Even with priority assigned to balancing computations, its location and turn-around time make it less than ideal for this application.

It is the writer's belief that the most desirable approach toward establishing computerized production balancing involves a prior decision that a standardized balancing procedure will be adopted which is devised to fit the needs of a computer method, so that in turn the computer program can be designed to dovetail with this procedure and to avoid excessive complication and flexibility. The author has not touched upon these implementation topics which, although they are not related to the basic mathematics of a computer program for balancing, do bear quite importantly on the design of the program as a whole. The author's comments on them, reflecting his own approach and experience, would be of great interest.

Author's Closure

Mr. Heymann's discussion is a valuable addition to the paper, in that it shows some of the many possibilities for useful additions to a least-squares computation procedure.

In the author's view, the goal of the computations should be to provide the maximum amount of useful computed information, so that the engineer in charge of the balancing program is in the

[2] Development Engineering, Steam Divisions, Westinghouse Electric Corp., Lester, Pa. Mem. ASME.

most favorable position to use his engineering judgment in selecting correction masses. Mr. Heymann's suggestions for additional computations are a worthwhile contribution in this direction.

The computation procedure described in the paper does not provide for different initial weightings of unbalance readings at different locations, speeds, and loads. However, a subsequent modification makes it possible to compute balance corrections on the basis of selected locations, speeds, and loads, while still computing the effects of the corrections at the other locations, speeds, and loads as well. As Mr. Heymann suggests, a more sophisticated weighting procedure would also be possible.

In answer to Mr. Heymann's three specific questions:

1 The least-squares computation procedure was an outgrowth of a previous trial-search computation procedure developed by balancing engineers, for which complete trial data were customarily obtained. The computer inputs and outputs are the same for the least-squares computation procedure as for the previous trial-search procedure.

2 The computer input sheets were designed by the balancing engineers who furnish the data and use the results.

3 The computations are performed on a high-speed digital computer which permits a high-priority program such as this one to interrupt a lower-priority program without losing results already obtained in the lower-priority program. Thus, the computer inputs can be brought over from the test floor or telephoned in from the field, and the results can be reported back a few minutes later.

With all the modifications that are possible to the least-squares computer program, it should be reiterated that the most important single piece of information it provides is the RMS residual error (R) of the first iteration. This number is a lower limit to the maximum residual vibration that can be achieved with the combination of speeds, loads, pickup locations, and balance planes under consideration.