What's Wrong With My Balancing Instrument?

By Victor Wowk, PE, Machine Dynamics, Inc.

There is probably nothing wrong with the instrument itself. It is more likely that the method used was not the best, or some other mechanical defect exists in the physical system. The instruments are usually quickly, and erroneously, blamed when mass balancing does not produce good results.

My field balancing experience has not always been successful. Indeed, balancing with a test rig can produce poor results if the test weights are placed in an adverse location. This will be demonstrated in this article. Mass balancing is mostly science, but there is some art and speculation in the methods. The art lies with the strategy of choosing a method of balancing. The speculation is in the placement of the test weight. This is a good career field to satisfy that gambling urge, since placing test weights on a spinning rotor is much like placing bets in roulette, with the exception that the odds are in favor of the balancer.

Instruments

There are two basic instrument systems for measuring the amplitude and phase at rotating speed: The tuneable filter and the spectrum analyzer. The tuneable filter is an analog instrument (Figure 1).

The vibration sensor measures the oscillation of the bearing support, or other stationary object, as the imaginary heavy spot rotates. The sensor also detects any other vibrations transmitted to that measuring location. The instrument is tuned to the rotating speed, in the hopes of eliminating all external effects except for the unbalance force that is synchronous with rotation. The tuning is done with a circuit very similar to radio receivers. This circuit brings into resonance an electronic circuit that also amplifies the signal from the sensor. It therefore filters and amplifies the vibration signal to achieve a relatively clean sine wave. This sine wave is displayed on an AC voltmeter for amplitude, and simultaneously is used to flash a strobe light via a comparator circuit. This is shown schematically in Figure 2.

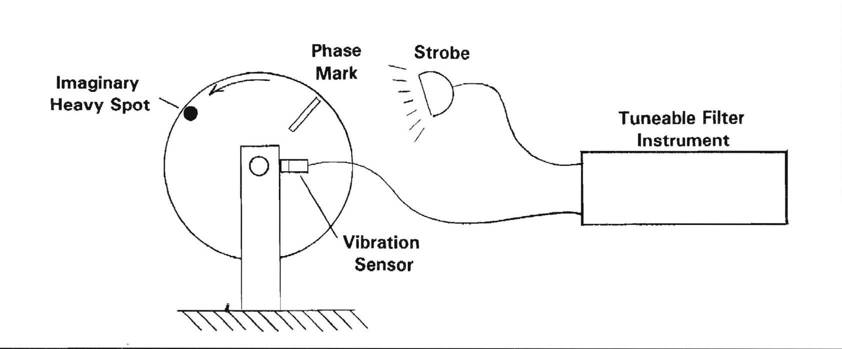

Figure 1 (Top) - A tuneable filter instrument set up for balancing.

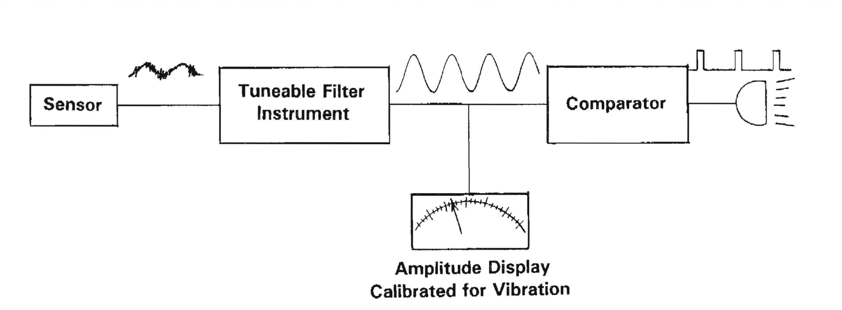

Figure 2 - Functional block diagram of a tuneable filter balancing instrument.

The comparator circuit sends a pulse train to the strobe light trigger circuit, typically at the negative to positive crossover point of the sine wave, With this instrument system, the source of the amplitude and phase measurement comes solely from the vibration sensor. It is difficult to fool it. It is not that you would want to fool it, but sophisticated electronic instruments, especially those measuring low voltage levels, can detect extraneous noise or generate some of their own, at no extra charge. The tuneable filter balancing instrument has been in use for at least 50 years. It is a mature system; reliable, field proven, very fast, simple to use, and not sensitive to small speed changes if the filter is retuned. Also, the direction of rotation of the rotor is not relevant.

The spectrum analyzer for balancing is a younger system. It is a digital system, and therefore, subject to digital processing anomalies which will not be covered in this article. The analyzer needs to have two sensors to measure phase. The second sensor is typically a photosensor detecting the passage of optical reflective tape. The instrument setup is shown in Figure 3.

The analyzer detects phase by measuring the time delay from the photosensor pulse to the vibration signal. This time difference is divided by the total time for one period of rotation, and multiplied by 360°.

$$\text{Phase} = \frac{t_1 - t_0}{T} \times 360^\circ$$

t_0 = time of photosensor pulse
t_1 = time of vibration signal peak
T = time for one complete cycle

The analyzer displays the phase in digital degrees from zero to 360. It cannot measure angles at all, but it can measure time very accurately. Therein lies its weakness, because small speed changes in the machine create huge phase changes unless the analyzer has a built-in tracking filter, or something that simulates one like a frequency multiplier to adjust the analyzer clock frequency, or a phase locked loop.

The spectrum analyzer, as a balancing instrument, is more sensitive to setup errors. It is slower than a tuneable filter instrument, both in set up and in acquiring data of amplitude and phase. It is more difficult to use with more front panel controls, and generally is a more sophisticated instrument. It requires stopping the machine to attach optical tape and to set up a photosensor. The direction of rotation of the rotor is of paramount importance for placing weights. It is not as field proven as the tuneable filter instrument, but it is capable of measuring amplitude and phase to greater precision, and capable of producing better balance levels. It is a safer measuring system for the balancer since he/she does not need to gain visual access to the rotor to strobe it. The access doors can be gently closed on the cables and the balancer can be safely positioned across the hall or outside in a pickup truck, whatever the cable lengths will allow.

Both the tuneable filter and the spectrum analyzer are capable of producing equivalent balance results. Which one to use boils down to a decision of what is available at the time. Which one to purchase depends on budget and the skill level of the balancer. There are many tuneable filter instruments in the field which testifies to their utility.

The Influence Coefficient Method

The influence coefficient method is a matrix calculation. The inputs are vibration amplitude and phase in the original condition and with test weights on board. The output of the calculation is the amount and location of correction weights. The goal is to drive the original vibration to zero. This has never happened for me. There is always some residual vibration remaining, leading me to believe that the method is not perfect. This "balancing by the numbers" is like flying on instruments. Physical insight is often lost, especially for two planes.

The influence coefficient method has its roots with Thomas C. Rathbone in 1929 for single plane, and Ernest L. Thearle in 1934 for two plane. The method is mathematically elegant and theoretically sound. It works well in practice when conditions are ideal. These conditions are:

- The physical system has no other mechanical defects.
- The synchronous amplitude and phase response are linear.
- The test weights are placed in locations that create a well-conditioned matrix.

These conditions do not always exist in field balancing. When that happens, the correction weights do not reduce the vibration sufficiently. It does not converge rapidly to a smooth-running condition with successive trim balance weights. It could even diverge and get worse. All along, the instruments are operating perfectly in acquiring amplitude and phase, and the operator is following the same procedure that has worked before. The I.C. method is flawed. The symptoms of things not working well are:

- Little or no phase changes with test weights.
- Unusually large calculated correction weights for the size and speed of rotor.
- Fifty percent reduction in vibration not obtained with the first correction weight placement.
- Trim balance calculations call for successive larger weights.

These are the symptoms of an ill-conditioned matrix. Everett has demonstrated the effect and Darlow has documented a test for detecting an ill-conditioned matrix.

The deleterious effects seem to be compounded when more planes are involved. Consequently, single-plane balancing seems to work better and more consistently in the field than two-plane balancing.

Tests

I have observed the demonic effects of I.C. balancing not working during field balancing and usually promptly switch to another method. More recently, during classroom balancing exercises, two different groups had opposing results on the very same practice machine, with the identical original unbalance condition, and using the same instruments. There were only three variables:

- Seven days time lag
- A different group of personnel
- Trial weights placed in different locations

One group achieved a better than 90% reduction in vibration at both bearings with the very first placement of correction weights. The vibration got worse for the second group. I decided to investigate.

Two controlled tests were conducted, one for single plane and another for two plane. The single-plane test was simple—a trial weight was placed every 30° and the amplitude and phase measured. The measured data at each position was used to calculate the single correction weight. The data is tabulated in Table 1 on the next page.

This single-plane balance test shows some very interesting results. First, the lowest vibration was obtained with the 4.25-gram test weight placed at 120°. The amplitude of 8.0 millivolts is very low, and this is obviously close to the best amount and location that the correction should end up at. However, only the trial runs with the test weight at 90° to 270° resulted in good calculations. The remaining half of the trial runs on the other half of the disk resulted in poor calculations. One run at 60° was grossly in error, calling for a 90-gram correction weight. The second time around it showed some change in phase, and called for only 7.9 grams of correction weight. But this is still in the wrong location at 142° and twice the "correct" amount.

The conclusion to be drawn from this test is that when phase measurements do not change much, the calculated correction weight is likely to be in error. The influence coefficient method is sensitive to the placement of the test weight. This is the gambling side of balancing.

Another test was done with two-plane balancing to examine the sensitivity of trial-weight positions. Some original unbalance was introduced in the two planes of the test rig shown in Figure 4 on the next page. This original unbalance remained constant for all five test runs. The only variable was the placement of the test weight. The test weight itself remained constant at 4.7 grams. The first four runs placed the test weight at 90° positions, with the far plane location at 180° opposite to the near plane. After seeing the poor results at 90°, then the fifth run placed the trial

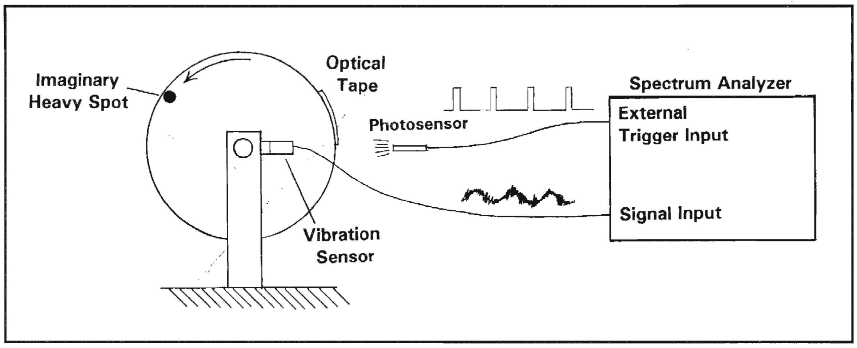

Figure 3 *- A spectrum analyzer set up for balancing.*

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Table 1 - Single-plane Balancing Test, 4.25 Grams Test Weight

Test Weight Position	Millivolts, Amplitude	Phase	Calculated Correction Weight with Influence Coefficient Method		Comments
Original	**46**	**-110°**			
0	83	-123°	4.9 gr	152°	
30	69	-95°	7.2 gr	251°	
60	48	-110°	90.0 gr	217°	Very bad
90	26	180°	4.4 gr	123°	Good
120	8	70°	3.6 gr	120°	Good
150	29	-20°	3.6 gr	118°	Good
180	51	-40°	3.5 gr	121°	Good
210	69	-60°	3.7 gr	122°	Good
240	84	-80°	3.9 gr	118°	Good
270	92	-90°	3.8 gr	128°	Good
300	94	-80°	3.3 gr	173°	
330	92	-90°	3.8 gr	188°	
360	83	-110°	5.3 gr	178°	
30	68	-100°	8.1 gr	239°	
60	49	-140°	7.9 gr	142°	

weight at 50° in both planes. This made it worse.

The correction weights were calculated for each run and a verification run was made to measure the resulting vibration with the correction on-board. The data is shown in Table 2.

Table 2 has many numbers, but a critical examination shows that the influence coefficient method is flawed. Runs 1, 3, and 4 had good vibration results with somewhat different weights. This suggests that there is more than one solution in two-plane balancing. Run 2 had fair results but not as good as the others. The weight set in Run 2 was grossly different than the other runs, but it still achieved a fair improvement in vibration. It appears that the I.C. method can converge to more than one solution, and which solution it heads for depends on the trial-weight placement.

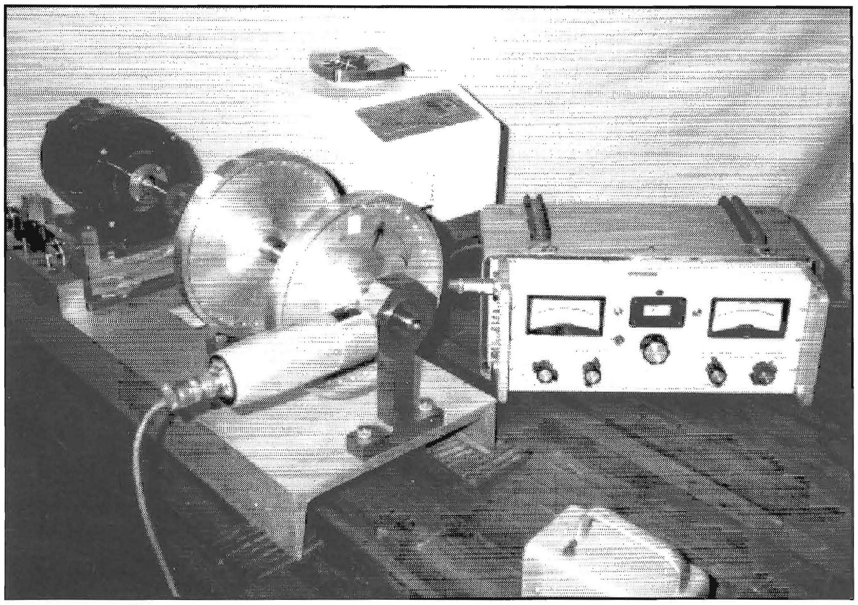

***Figure 4** - Test rig for two-plane balancing test.*

Run 2, with its less-than-ideal results, suggested doing a fifth run with the trial weight at 50°. In addition, the 4.7-gram trial weight did not flip 180° when doing the far run. It remained at 50° for both runs. This is typical for two-plane balancing, i.e., to leave the trial weight at the same angular location. The results for Run 5 were very bad. The vibration got worse. The correction weights were unusually large. A trim balance calculation requested even more weight in similar locations. In other words, it was not converging to a solution, but actually diverging. This "balancing by the numbers" was causing a bad day. A flight instructor once told me that flying solo on instruments was like playing Russian roulette.

The conclusion to be drawn from this two-plane balance test is that the calculation is sensitive to trial-weight placement. The speed of converging to a smooth-running condition is strongly dependent on the placement of test weights. It may even get worse.

The Physical System

Mass balancing can only correct problems of unbalance. By placing weight on a rotating part, the center of gravity is adjusted to be coincident with the center of rotation. This procedure can be expected to have only limited success for canceling other sources of vibration at rotating speed. Some of these other sources are:

- A bent shaft
- Misaligned bearing
- Misaligned shafts
- Eccentricity of a power transmitting rotor
- Resonance

The first four of these other sources can be detected with a dial indicator during slow hand rotation. Therefore, at least one dial indicator, with magnetic base, should be in every balancer's toolbox.

The physical system of the rotor, bearings, and foundation must be mechanically sound for textbook balancing to work well. It works better on a balancing machine in a shop, but field balance situations are far less controlled, and the balancer is not given warnings of pre-existing defects. He/she may be given clues when good results are not achieved, and this is the time to get out the dial indicator and perform a physical inspection of runouts. The defects must be found and corrected independently of balancing. Mechanical systems, unlike biological systems, are not self-healing.

Strategies

Before choosing a plan of attack, it is best to assess the enemy. A field balancer who always uses the same procedure is setting himself up for an ambush. Some balancing methods work better than others under certain pre-existing physical conditions. These pre-existing conditions are unknown to the field balancer when initially approaching a problem. Therefore, two analysis procedures are recommended prior to starting balancing.

The first is to conduct a full survey. Measure the amplitude at rotating speed in three orthogonal directions at each bearing. This forces an analysis and helps determine where sensors will be placed for balancing. It determines which machine is at fault, and even which end of it.

The second procedure is to measure amplitude and phase at both ends of the machine to be balanced. This will decide whether single-plane or two-plane balancing should be attempted. Now a strategy for balancing this particular rotor can be chosen from the available list in Table 3 on the next page.

In addition to choosing an initial method which is more likely to succeed, the balancer can be adaptive and modify the method along the way. Let the knowledge obtained in the process steer the next step. For example, the balance planes can be changed to a different axial location where results look more promising. If the central plane does not produce improvements, then test weights can be moved to one of the end planes, or even to a pulley outside a bearing.

Another midstream strategy is to change the angular position of test weights. The previous tests indicated that some positions are favorable for influence coefficient calculations, and some positions are unfavorable. It is usually beneficial to place the two test weights 180° apart for two-plane balancing, but that decision should be deferred until after seeing the results of the first trial run.

A final strategy is to recognize when balancing is not working well, and it is time to get out a dial indicator, or check the foundation for resonances.

Conclusion

Balancing is mostly a science based on measurements and procedures. The process should always be driven by knowledge and not by habit. The instrumentation is rarely at fault when improvements in vibration cannot be made. It is most often other mechanical defects, and sometimes poorly chosen methods. The influence coefficient method is the fastest when it works. It requires linearity in amplitude and phase response, no other pre-existing defects, and favorable test-weight placements. The latter is mostly chance.

With all of these built-in setups for failure, why would anyone want to be a balancer? The fact is that most of us did not choose this career field when we were teenagers. We were unsuspectingly guided into it though some other path like vibration analysis or machine repair. However, once in the deep water, some choose to get out while others like the challenge. It provides instant job satisfaction, is a high-tech new technology, is fun sometimes, has opportunities for travel, satisfies that gambling urge, involves big dollars and crisis situations, can be physically demanding, will take you to high places including the CEO's office, and is a useful service to society.

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Table 2 Run 1	**Near End Amplitude, mils**	**Near End Phase**	**Far End Amplitude, mils**	**Far End Phase**	
Original	13.5	110°	8.5	70°	
Near T.W.	20.0	115°	15.0	110°	4.7 gr 350°
Far T.W.	8.4	90°	7.4	95°	4.7 gr 180°
Correction Weights	3.9 gr	209°	6.5 gr	192°	
Resulting Vibration	**1.3**	330°	**1.25**	310°	Good results

Table 2 Run 2	**Near End Amplitude, mils**	**Near End Phase**	**Far End Amplitude, mils**	**Far End Phase**	
Original	13.2	105°	8.6	85°	
Near T.W.	17.3	70°	11.7	65°	4.7 gr 90°
Far T.W.	12.8	130°	7.8	110°	4.7 gr 270°
Correction Weights	2.5 gr	61°	14.0 gr	211°	
Resulting Vibration	**3.9**	180°	**2.6**	190°	Fair results

Table 2 Run 3	**Near End Amplitude, mils**	**Near End Phase**	**Far End Amplitude, mils**	**Far End Phase**	
Original	14.0	105°	8.2	100°	
Near T.W.	6.8	75°	4.2	60°	4.7 gr 180°
Far T.W.	18.7	105°	13.5	95°	4.7 gr 0°
Correction Weights	7.7 gr	195°	2.1 gr	278°	
Resulting Vibration	**1.25**	0°	**1.3**	340°	Good results

Table 2 Run 4	**Near End Amplitude, mils**	**Near End Phase**	**Far End Amplitude, mils**	**Far End Phase**	
Original	13.5	100°	8.6	105°	
Near T.W.	12.4	140°	7.4	125°	4.7 gr 270°
Far T.W.	16.7	80°	9.6	70°	4.7 gr 90°
Correction Weights	5.0 gr	231°	4.8 gr	162°	
Resulting Vibration	**2.15**	155°	**0.85**	150°	Good results

Table 2 Run 5	**Near End Amplitude, mils**	**Near End Phase**	**Far End Amplitude, mils**	**Far End Phase**	
Original	13.2	110°	8.1	90°	
Near T.W.	20.0	100°	16.0	105°	4.7 gr 50°
Far T.W.	17.0	95°	12.2	85°	4.7 gr 50°
Correction Weights	8.5 gr	18°	22.8 gr	174°	
Resulting Vibration	**13.5**	30°	**10.2**	10°	Worse
Trim Add	9.1 gr	81°	23.6 gr	246°	

Table 3 - Available Balance Methods

Method	Advantages	Disadvantages
Trial & Error	Potential for good results when other defects exist	Time consuming
Four Run Without Phase	Quickly converges Always works Simple graphical calculations	Requires 4 starts and stops per plane
Seven Run Without Phase	Quickly converges Compensates for cross effect	Requires 7 starts and stops
Single Plane	Fast balancing when it works Applicable when phase is nearly the same at both bearings Graphical calculations Best for thin disks	Cannot compensate for cross effect Does not work well when other defects exist
Two Plane Influence Coefficient	Compensates for cross effect, couple, and static simultaneously Applicable when phase is more than 30° apart at both bearings	Requires computer to do I.C. matrix calculations Sensitive to test weight placement Does not work well when other defects exist
Static Couple	Useful when 3 balance planes are available Graphical calculations possible	Works better than 2 plane I.C. method on long rotors
Cleaning	Fast, cheap	None - cleaning is always recommended for a dirty rotor
Manufacturing Tolerance Control	Potentially smoothest machines Can make field balancing unnecessary	Most costly
Self-balancing rotor	Continuously adjusts	High cost initially

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About the Author

Mr. Wowk is the author of Machinery Vibration: Balancing, published by McGraw-Hill. This book will be available for sale at the Predictive Maintenance Technology National Conference, to be held December 1-4, 1997 in Dallas, Texas. Mr. Wowk will conduct a one-day balancing seminar at the Conference.