BHJ DYNAMICS INC.
PRECISION ENGINEERED HARMONIC DAMPERS

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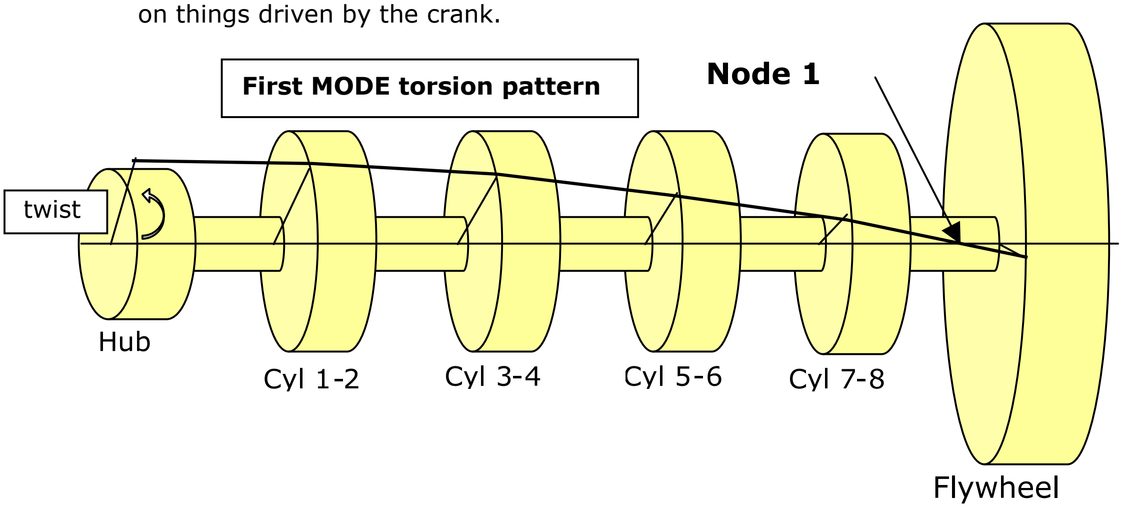
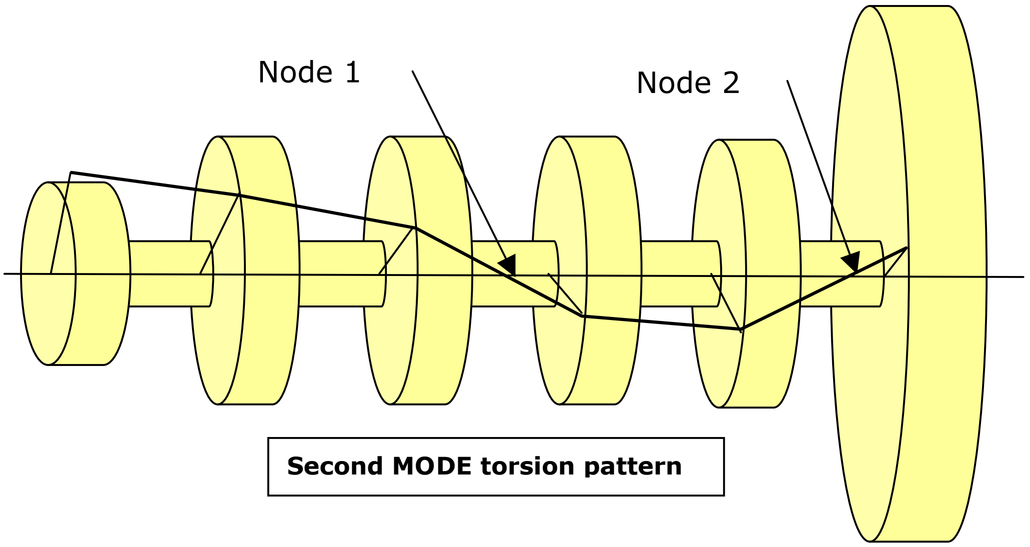
Crankshaft Torsion and Dampers

1. Torsion - The hidden problem with the crank system – and why it needs a damper.

- **First - Special words to know**
  - **Frequency, RPM, Orders, Modes, Nodes and Inertia**
    - **Frequency** - is how many things happen in a period of TIME = (cycles/second - called Hertz and abbreviated (Hz)). The crank natural frequencies are defined this way and are constants, they do not change with RPM.
    - **RPM** - is revolutions of the crank per minute
    - **Orders** - are defined as events per crank revolution. Because of this, their frequency is variable and goes up and down with RPM. Also, because the orders are in nice neat increments to each other, they tend to be confused with harmonics.
      - This is where the term Harmonic Damper creeps in, but is not quite technically correct. Harmonic is normally a time-based term (usually multiples of a base frequency) and orders are an event-based term. The damper is tuned to ONE frequency and damps the various orders as they excite the SAME frequency in the crank at different RPM.
    - **Mode** – describes a pattern of twist in the crank. Basically it describes the number of places the twisting motion changes direction from clockwise to counter clockwise.
    - **Node** – the name of the places where the crank vibration motion is zero as the motion changes from one direction to the other. (i.e. Second Mode motion has 2 Nodes)
    - **Inertia** – (also known as the polar moment of inertia) is the tendency of a mass to resist changes in rotation speed (RPM). It is mathematically the mass times the square of the distance of the CG of the mass from its center of rotation ($m \times r^2$). It is different from weight because the radius² factor makes it very sensitive to the diameter of the part. A thin flywheel has a much higher inertia than a long, small shaft of the same weight.

- **Torsion in the system. Where it comes from – why it's a problem**
  - Torsional vibration is twisting of the crank from one end to the other. It happens at fairly high frequencies (usually 250-400 Hz) and is driven by two different uneven torque pulses coming from the pistons. The angle of the twist is small, (up to perhaps 1.5-2.0 degrees in bad cases) but because of the high stiffness of the crank, it involves torques within the crank that are much higher than the torque that goes out the flywheel end to drive the car. The high frequency and high torques drive fatigue failures of the crank and high bearing wear as well as other side effects on things driven by the crank.





Second MODE torsion pattern

- Combustion pressure torques – each cylinder delivers most its energy in about 100° of crank rotation, and only every other rev in 4 strokes.
- Reciprocating component torques – each piston/rod applies a reversing torque twice /rev to accelerate/decelerate at TDC & BDC
- The crank masses and stiffness between cylinders have a built-in torsional frequency that will “ring” in a torsional manner just like a tuning fork. Think of this system as a stack of little flywheels, one at each crankpin location with a torsion bar (the mains) connecting them. There are usually two different frequencies present in the operating range of the engine that have different patterns (Modes) of twist.
- The first mode frequency has the whole front of the crank forward of the rear main twisting one way while the flywheel goes the other. This puts a dead spot (or Node) at the area of the rear main where the motion changes direction. This is also the point of highest stress and is usually where the crank breaks from a torsion-related problem.
- The second mode adds another dead spot (Node) somewhere in the middle of the crank and has both the front part of the crank and the flywheel going one way while the middle goes the other. Because the sections between the nodes are shorter, with the same stiffness between them, the second mode frequency is higher than the first mode.
- Both of these modes of vibration can occur together in the higher RPM ranges.
- Torsional vibration peaks occur when a frequency component of the piston firing and reciprocating torques gets close to one of the built in frequencies of the crank.
- When the inputs get close to a natural frequency, the system goes resonant and the twist angle gets magnified about 6–10 times the normal amount in a very sharp “peak” that is only a few-hundred RPM wide.
- This magnified twist is what does the damage in crank stress and bearing wear. It is dangerous in that it builds up fatigue stress cycles very quickly because it is such a high frequency. The vibratory torques at these resonant peaks can get much higher than the drive torque going out the flywheel.
- The first natural frequency of typical V8 & V6s are usually in the 300–450 cycles /second range.
- These vibration peaks happen at several different RPM points in the RPM range of the engine. Not only are the firing and inertia forces driving at different basic orders

(½ /rev and 2/rev per piston for a 4 stroke), but also the distorted shapes of those torque pulses contain multiple torque components creating the other Orders.

- The multiples in the shape of the torque pulses are called order content. It is sinusoidal pieces of the torque pulse that are related to how many times/rev each piece happens. (½ - 1 - 1 ½ - 2, etc.)
- Some orders (the lower ones) are stronger than others and that is determined by the shape of the torque pulse and the firing order of the engine
- The end result is that each natural frequency of the crank can get driven into resonant peaks by several of these orders as the engine runs through the rev range. There are usually 3-4 big peaks and lots of smaller ones.
- The good news is that the peaks in an engine <u>without a damper</u> are <u>usually</u> ALL THE SAME FREQUENCY unless the engine revs very high. This is normally the first mode frequency of 300-450 Hz as mentioned above.
- The second mode frequency of the crank is usually 1.5-1.8 time higher than the first mode and is usually high enough that is does not have peaks in the normal rev range.
  - The exceptions to this are long engines (inline 6s and 8s) and or engines with unusually low natural frequencies (flexible cranks or very heavy reciprocating weights – think marine ship engines)
  - A second exception, are engines with very high RPM ranges. (Think Indy or Formula 1 types)
  - (A typical torsion map of an automotive V8 engine is shown on page 7.)

- **How the damper works to reduce crank torsion.**
  - In its simplest form, the damper is just another mass (the inertia ring) and a spring (the rubber strip) tuned to a single frequency. This is added to the crank system at the end with the most torsional motion. (the end opposite the flywheel). The damper motion always lags behind the motion of the crank and imparts a lagging torque to the motion of the crank vibration and also absorbs some energy from the crank motion as the rubber strip flexes back and forth.
  - The damper is tuned to go into resonance at a frequency between the two main crank frequencies. (Although those two frequencies have lowered a bit due to the added mass of the damper on the front of the crank system.) The crank twist is <u>reduced</u> by the lagging damper torque and energy absorption, and the damper ring's twist motion on the rubber <u>increases</u> in the bargain. The trade-off is that the damper becomes the highly stressed part instead of the crank.
  - The tuning frequency of an OEM damper is typically specified with a tolerance of about +/- 8% at a temperature of 150°F and a motion input similar to the operating crank vibration (+/- 0.1° applied to the hub). It must be done this way because the temperature and the amount of motion in the rubber both affect the dampers' frequency.

2. Damper Characteristics

- What things make any difference to the dynamics?
  - The crank, looking out at the damper fastened to its nose, can only really "see" 5 things.
    - The size (inertia value) of the damper ring
    - The tuned frequency of the damper (whether it is reasonably correct or not)
    - The damping built into the rubber composition (high to low)
    - The parasitic inertia of the damper hub. (the hub becomes an added inertia to the crank system and more hub only makes the damper's job more difficult)
    - The weight of the damper. This is most important when sideways bending of the crank nose is considered.

- How these 5 things happen is "invisible" to the crank. It does not care about cast vs. billet metals or what shape the damper is. All the other details of the damper are aimed at secondary things like driving accessories, low cost, light overall weight etc.
- Balance – The damper is no more of a "balancer" than an ordinary belt pulley would be. Nothing about the resonant motion of the inertia ring /rubber construction does anything for balance. The damper is balanced to a neutral specification for internally balanced cranks and may incorporate a bobweight for externally balanced cranks. BUT, the balance is a completely separate function from the torsion control.
- SFI Certification – The widely advertised SFI certification is a safety issue that has nothing to do with the damper's ability to control torsion. SFI basically specifies wrought (billet type) materials and an assembly method that traps the inertia ring from coming off the hub should the rubber fail. The SFI proof test is a high-speed spin test (with no torsion input) for a certain amount of time with the damper mounted, as it would be on the engine. While this certifies that the damper will not burst from centrifugal force, it says nothing about whether the damper was properly sized and tuned for a particular engine.

- **Tuned Rubber Dampers**
  - The tuned rubber strip type damper is easily the most popular in the OEM world and the aftermarket for several good reasons.
  - It is the most weight-efficient design
    - It has its entire supporting hub on the inside and the entire working inertia ring on the outside. This is as good as it gets for weight and inertia distribution.
  - It is the most economical to build
    - There are only 3 major parts with only a few critical-dimension surfaces. The rubber strips can be economically molded as straight parts. It's easy to put together if you know how to build the tooling correctly, impossible if you don't. (That rubber strip is really compressed in there very tightly) (No, its not "poured-in" or hammered in with a screwdriver.)
  - Properly designed, it is effective, reliable, and long-lived.
    - The width, thickness and placement of the rubber relative to the size of the inertia ring as well as it's chemical compounding and hardness is all-important to the total design. Getting the right inertia in the ring, the right tuning, and controlling the stresses is far more difficult than it looks.
  - Hybrid designs, with enclosed inertia rings easily solve the containment of the ring for SFI purposes, but pay a high weight vs. effective inertia penalty with the large enclosing hub structure.
    - They can offer user rebuild-ability with O-ring construction at the price of higher specific stress on the rubber, and tuning changes are easier, if you know what you need.

- **Viscous Dampers**
  - The viscous type damper is a popular alternative to the rubber element type and operates in a slightly different manner.
  - The inertia ring is completely enclosed in the housing and surrounded with a very thin layer of high viscosity fluid. (usually silicone based)
  - The inertia ring is free to rotate (back and forth), and it too lags the crank torsional motion and applies a lagging torque to the crank nose. The ring motion running back and forth in the housing shears the fluid and the fluid absorbs energy from the crank motion similar to the way a rubber strip does as it flexes.
  - The biggest difference is that the inertia ring does not go resonant at any frequency and is thus not "tuned" like the rubber damper.
  - There is, however, a best dynamic stiffness where the damper works best. This is controlled by the viscosity of the fluid and the clearance between the housing and the inertia ring.

  - These dampers tend to be less frequency sensitive and have a very long life when properly designed. Their ability to absorb large amounts of energy makes them the best choice when the engine gets big. They are the best choice for truck and marine diesels.
  - They do have limits and some downside for the smaller engines.
    - They are heavier than a rubber damper for a given capability,
      - The housing inertia is all parasitic "hub"
      - The ring's effective inertia is only half of its measured inertia. The physics of the system places half the inertia to the active side controlling vibration and half to the hub side as even more parasitic inertia.
      - The life of the viscous fluid is not infinite. Under prolonged heat and shear loading it can break down chemically and leave the ring too "free". It can also get contaminated with bearing wear particles. The problem is, there is no good way for the average user to detect this other than sawing the damper apart. The big dampers in ship engines have samples of the fluid taken periodically and an analysis is run to determine the condition of the fluid. The big dampers are take-apart rebuildable.
      - Another failure mode is that the bearing materials between the ring and housing can fail and the ring "locks up" solid to the housing. Then you have a really heavy dead weight pulley. Again, there is no easy way to detect this for the average user.
      - Third, the housing must not be dented via poor handling, the clearances inside are only in the 0.010 range and dents can "trap" the inertia ring and lock the damper.

- **Pendulum Dampers**
  - These dampers have rollers placed in holes in the damper hub, drilled parallel to the crank axis.
  - The rollers are a loose fit in the hole so that they are flung to the outside of the hole by centrifugal force but are free to roll back-and-forth sideways when the hub is oscillated by the torsional motion of the crank.
  - The roller clearance is chosen to set up the "tuning" of the rollers as they roll up one side of the hole and then the other. This makes the rollers act similar to the inertia ring of a rubber damper and provide a lagging torque to the hub and back to the crank.
  - There are two major differences from the rubber damper.
    - The centrifugal force on the rollers makes them "heavier" as the damper spins faster and in effect raises the tuning as the RPMs increase. This tunes them to higher frequencies as RPM rises.
    - This has the effect of tuning the rollers to a certain ORDER rather than a certain FREQUENCY. Fairly clever and it's why the aircraft people who have narrow RPM ranges have used them for a long time. You can even tune different rollers inside the housing to different orders, but then, you are dividing the available damping mass between the orders.
    - The rollers have very little damping (a little friction and maybe some minor viscous action of a little lube oil) and thus don't absorb much energy from the crank vibration. This lets them run cooler and have no heat related tuning changes
    - The dampers also tend to have a high parasitic inertia relative to the active roller inertia because of the housing required to contain them.

3. Crank Variables.

- **Common variables and the trends**
    - Steel vs. Cast – The steel cranks will have frequencies a few % higher because of higher material stiffness (approximately 10 %) than an equivalent cast crank.

- Stock vs. Stroker – Stroked cranks tend to have a little lower frequency because the crankpin/web areas are not as stiff. The main/crankpin overlap is less, and they have a little more weight (hence, rotating inertia) in the counterweights to balance the increased stroke.
- Crank Pin Diameter - Crankpin diameters don't tend to change the frequency as much because the lower stiffness is offset by lower inertias of the pin itself and the rod big end. Stresses however are generally higher. (smaller pin and less overlap)
- Main Bearing Diameter – Larger mains increase the frequencies via higher torsional stiffness and vice versa.
- Internal vs. External Balance – Internal balance generally means heavier counterweights overall and lowers frequency a bit. The bending stresses are generally better distributed. External balance is usually done to lighten the crank as the weight needed to get the end-to-end balance moment is moved as far as possible to the outer ends of the crank.
- Heavy Metal Bobweights – Pretty much same effects as internal balance.
- Light Pistons – This reduces the reciprocating torques and takes a little weight out of the bobweights. It makes more difference at the higher RPMs.
- Short Rods/Long Rods – This has some effect on the shape of the reciprocating torque curves but not much effect on torsion overall. Again, more effect at very high RPM.

4. Other Rotating Group Parts

- Heavy vs. Light Flywheels – Light flywheels lower the whole system inertia, move the high torsion stress point a little farther forward (away from the flywheel), raise the first mode frequency a bit, and sometimes allow a little smaller damper. They also allow more crank lugging motion which usually shows up as gear rattle in the transmission. (This is called "rigid body motion" in the torsion trade since the crank is just seeing RPM variation without twist)
- Light vs. Heavy Pulleys – Heavy pulleys are just more parasitic inertia at the light end of the crank and make the damper's job more difficult. They lower the frequency a bit but make the crank seem larger to the damper; i.e. a larger damper ring needed.
- Blower Drives – Mechanical blower drives for Roots type blowers can actually help the damper by acting as more damping at the front of the crank. Mechanically driven blown engines generally are no worse, torsionally, than normally aspirated. Turbos usually are worse.
- Dry Sump Drives – Not much effect other than some torque required to drive the pump.
- Cam Chains – Cam chains can take a beating from the torsion peaks. Same for cam gear drives. The vibration motion tries to make the cam drive do the same motion and jerks the chain back and forth. If this motion gets through to the cam, it doesn't help cam dynamics and can also show up in the spark scatter with cam driven distributors.
- Spark Scatter – If the spark is taken off the front of the crank, the torsion motion is in the trigger wheel as well. The best place for the trigger wheel is near the rear of the crank where torsion motion is smallest. (guess where the OEM's are putting their sensors now)
- Transmission Gear Rattle – This is mostly caused by low frequency torque pulses ("rigid body motion") in the crank at lower speeds when flywheel energy is low, although this motion usually persists out as far as 2000-3000 RPM. Aluminum flywheels make it worse for the obvious reason. These frequencies are way lower than the damper is designed for and the damper has virtually no effect on the gear rattle problem. Dual mass flywheels go after this problem.

5. The Damper/Crank-nose Connection.

- Dampers on any performance engine need to be fastened really tight to the crank nose. Most need the combination of a press fit plus a good tight crank bolt. The key has little torque capability by itself and will quickly fail if the press fit/clamp load cannot carry the damper and accessory drive torques.

- The lagging torque generated by the damper when it is controlling one of the torsion peaks can easily be 200–300 ft. lb. and the torque from a big damper tuned high for a high RPM big block can get toward the 1,000 ft. lb. range.
- It is not uncommon to see fretting at the back of the damper where it buts against the timing sprocket or crank shoulder. This only means the damper is actually slipping on its mount and cannot pass all the torque back to the crank.
- Think of the key as nothing more than an indexing device for the timing marks or ignition wheel, it won’t keep the damper on by itself.
- Short bolt/Long bolt
  - Putting a bigger diameter bolt into the crank nose might help hold the damper tight but may actually go the wrong way in the end. The bolt clamp load serves to pull the crank nose into the damper hub and leave the crank with a tension stress back at the end of the bolt threads or the back of the damper hub right at the end of the keyway region. All too often this can contribute to broken crank noses.
  - The best solution is to move the damper bolt threads back into the main or even the first crank web, put in a long high grade stud and tighten that to the maximum. This give lots of bolt stretch for heat expansion compliance and leaves the crank nose neutral or in compression rather than tension. (Don’t do this without checking to see where the oil hole for the main is located)

6. Damper vs. Engine Application.

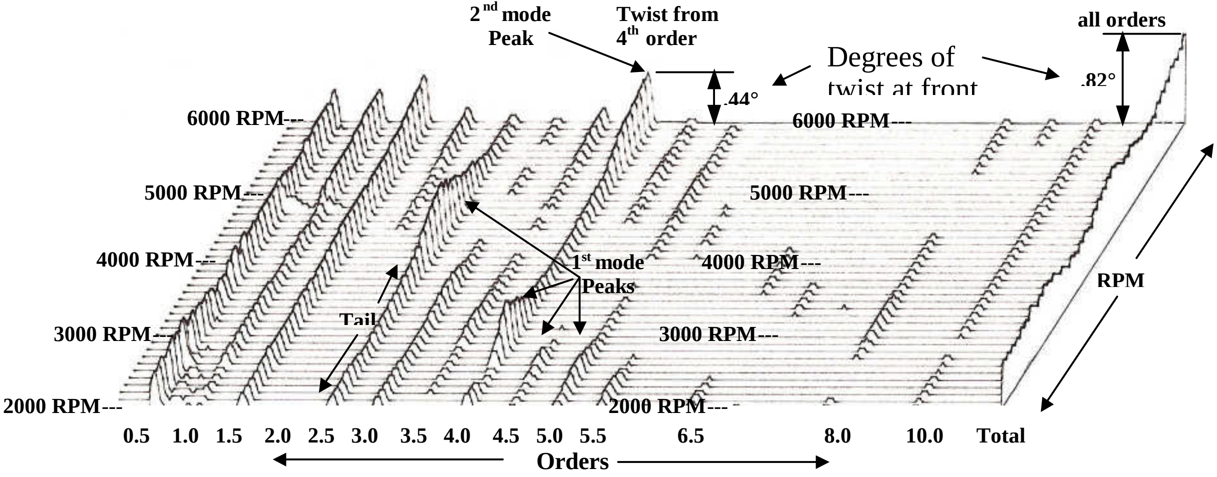
- The damper is tuned to give the best compromise of low torsion across the RPM range that the engine sees at high loads. That means that the intended use of the engine has a great affect on what the best damper/tuning will be.
- OEM dampers are usually tuned to reduce torsion most in the low to mid range, where the engine spends 99% of its life. This may leave some higher torsion near redline, but very few production engines live their life there. This choice is also why some large, low-RPM V8’s got away with no damper at all.
- Even modified street engines may be only a little different than OEM in their overall operating envelope when the time spent at various RPMs is considered.
- Racing is another story. Crank system changes may alter the crank natural frequencies a bit (usually in the +/- 10%-15% range), but the real changes are in the operating envelope.
- The usual problem is that the higher RPM ranges have both first and second mode frequencies present. The peaks of both can even overlap each other at the same RPM. Since the damper is only tuned to one frequency, the tuning may have to be compromised upward to do a better job on the high frequency second mode peaks. This is what drives the common rule of thumb “high performance dampers are tuned higher”.
- It’s a common perception that higher RPM is a mandatory connection to higher tuning. Not really. The higher second mode was always there, the RPM window just moved upward enough to expose them and force the damper tuning to consider both frequencies.
- Heat is the ultimate enemy of the rubber damper and the power absorbed (and heat generated) goes up with the square of the frequency. Thus, it doesn’t take too much upward shift in the tuning (40%) to double the heating tendency of the damper.
- Strain (the distance the rubber flexes back and forth) is next most important and the rubber must have adequate flex life capability to cope with this. Rubber compound technology is everything here.
- The OEM’s spend a lot of time developing the rubber for heat and flex resistance. Lab life tests can run from hundreds to thousands of hours. Traditionally, they have used at least 5 different rubber compound “families”. They are, in rubber terms: Natural (NBR), SBR, Neoprene, EP, Nitrile, and Poly-Acrylics. All have strengths and weaknesses and are chosen for the best match to various designs and engine usages. They guard their

compounds and sources, sometimes producing the rubber in-house for proprietary reasons. No OEMs use silicone to my knowledge.

7. Aftermarket R & D

- The question of how a damper manufacturer takes all these things into account to design for an aftermarket application is a complex one.

Crankshaft Torsion Map of typical 350 cid V8



- One way is to take measurements of representative engines with an instrument called a torsiograph. This tells where all the peaks are in the RPM range, how high and what frequency they are. The graphical output is a 3D map that looks a lot like a fuel or spark curve map. (An example is shown above)
- A few dampers sized and/or tuned differently pretty quickly show the best combinations. This can be done in a day or two on the dyno, but is not exactly cheap. Torsiograph equipment goes for around $30,000 if you buy it, $500 - $1,000 a day if you rent it with an operator and dyno time is $1,000 a day or so. Don't forget the price of the motor and experimental dampers and the fuel.
- A second method is to use computer models of the engine and run the engine/damper combinations on the computer. Once set up, this goes fairly fast and is usually accurate within 10%-15% unless the engine model has been adjusted to agree with data from a real engine test. Then the accuracy gets to a within a few %.
    - Even the best of computer models still have trouble with predicting running temperatures and changes in the rubber characteristics with changing temperature and motion.
    - Another problem is getting good cylinder pressure curves. This is hard to do right and thus expensive. Many times, the only alternative is to use "generic" data or curves from another engine.
    - Computer programs for doing this modeling are presently available, but not cheap, and only available from some of the big developers such as Ricardo and AVL. Other big OEM companies have proprietary in-house programs, but will not sell them.

- The laboratory testing rig for doing a frequency-damping-temperature test on a damper runs the OEM's about $50,000 to $100,000 depending on the amount of computer automation. How many aftermarket makers have made this commitment?

- The typical OEM requirement (in addition to an engine torsion test) is a life test that is some combination of time/heat/dynamic load that simulates at least 100,000-mile durability. It typically takes 1,000 hrs. of lab time to do that simulation on several parts to get OEM approval. Again, how many aftermarket makers attempt this?
- Torsion data and curves on various engines
  - These are hard to find; not because they don't exist, but because the folks who pay the price for that data then OWN the data and are mostly reluctant to show that hard-earned knowledge to the world (their competitors).
  - Most of the curves you see in advertising are very stripped versions of the whole picture. It is fairly easy to pick the portions of the data that give the best-looking results. Don't look for much in the way of identifying labels of orders or totals. (Totals are the motion of all the orders added together; significant because the engine sees all that motion as a whole)
- Having said all that, there are some good aftermarket designs that perform and survive. The good ones do more homework than the copycats. How many offshore copiers are running dyno tests or any durability testing? Let the buyer beware. Don't be afraid to ask them about how they do their homework. Good luck trying to get any data. Most of them hide behind the curtain of "proprietary information" when asked about design or testing. I have seen instances where that means they don't have a clue.

8. Crankshaft bending vibration.

- The control of bending vibration at the nose of the crank has only recently (10-15 years) been addressed seriously, even by the OEM's.
- This bending is driven mostly by the firing force of the first cylinder(s) behind the first main. The force tends to drive the crankpin down and the webs bend sideways like the legs of a bridge. As the force stops, the legs spring back. As a result, there is a rocking motion through the front main that makes the nose of the crank move in the opposite direction to the springing of the first pin. This leads to a vibration caused by the nose of the crank bouncing up, down and sideways. I have seen this get so severe in diesels that the viscous dampers have the internal inertia ring friction-welded to the case making the damper totally lock up. In modified racing engines, it is generally a broken crank nose. In general, heavy pulley or damper packages just aggravate the motion and do nothing to control it.
- The rubber damper has some damping effect on this by default since the inertia ring has a couple of degrees of freedom (motion) that react in that direction. This is true as long as the damper does not have a large heavy belt pulley attached to the front that overwhelms the size of the damper. Some OEMs have even added a second inertia ring tuned to react sideways to counter this motion. (Toyota for one) Others have found ways to reshape the ring and rubber to make the damper tuned differently in different directions (Metaldyne for one). (look up patent # 5,231,893)
- Although this is currently done more for noise reduction than crank reliability, there may come a point where the racing aftermarket has problems that can be helped with this technology.
- The viscous dampers and the pendulum dampers have very little chance at helping with this since they are not designed to have a motion reacting to the bending.

9. The bottom line for the man on the street for aftermarket dampers.

- Choosing the best damper for the application.
  - If you have any engine that can and will be run for long periods of time as street transportation, you can run the OEM damper with pretty good confidence that it will do as good or better than an unknown aftermarket. If you want something that is simply better looking and perhaps more resistant to having the ring come loose, use an aftermarket designed as an OEM replacement that has more "bling" or some ring

  retention feature incorporated. How well done these dampers are for function depends on how well they have been engineered or tested.
- If you are going to actually race, the choice probably divides into 3 classes.
  - **Short life engines.** Drag racers are typical short timers that get torn down and rebuilt so often that the question of durability from torsion problems may not be a consideration. If you have the facilities to do dyno testing, use the damper that gives the best power and has SFI approval.
  - **Durability engines.** If you are running an engine that you want to last awhile, (circle track, road racing, marine) then it is worth asking around and seeing what works for people building those engines or having a proper torsion test done to see what damper really does the job. A torsion test can be done on an engine dyno or a chassis dyno with the right equipment. (you can bet the NASCAR guys don't just guess about this)
  - **Really unique engines.** Doing dampers for old classic engines, or ones that don't get used much for racing can be a problem. It usually means selection via the dyno cut-and-try method or modeling the engine and designing from scratch.

10. Testing and Validation.

- Some aftermarket damper manufacturers and some engine builders have torsiograph equipment and can do torsion testing and can fine tune dampers for an engine for a fee.
- For true custom designs, BHJ, for one, has the ability to do both computer engine modeling & simulation and torsion testing on a dyno. Again, this isn't free, but what's that engine worth to you, even just a rebuild, especially if it breaks a crank?

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